Using Jet Correlations to Uncover Higgs Physics at the LHC

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Brookhaven National Lab - eRHIC group - September 18, 2014

Outline & Motivations

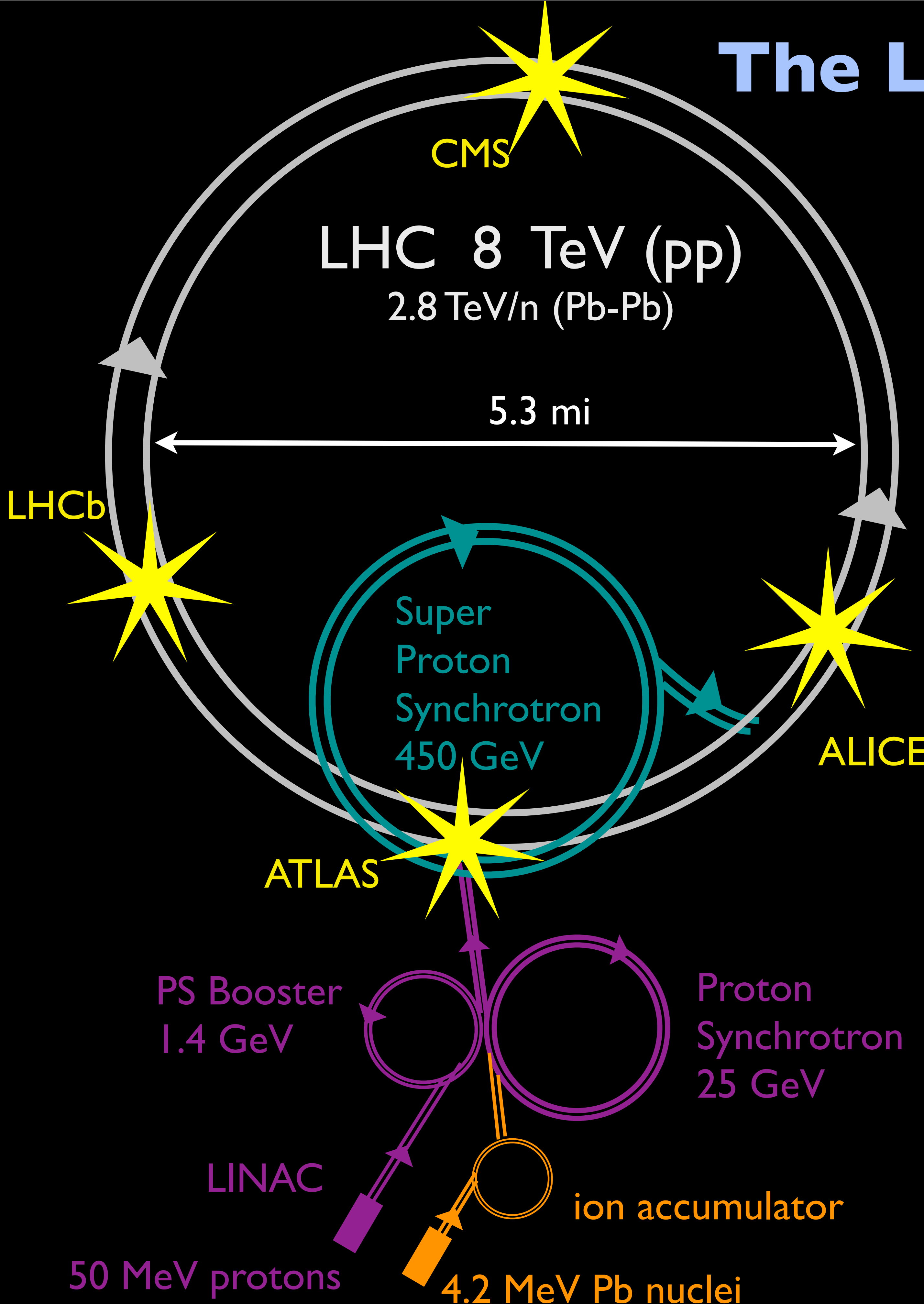
A Higgs-like boson has been discovered - is it the Standard Model prediction?

=> measure couplings, spin, mass, rates

=> forward - backward jets key

=> we seek to improve the Higgs analyses of ATLAS and CMS by including more signal events using Fox - Wolfram Moments

The Large Hadron Collider



Run 1 : 2010-2012

- ATLAS

$$\sqrt{s} = 7 \text{ TeV} \Rightarrow 4.5 \text{ fb}^{-1}$$

$$\sqrt{s} = 8 \text{ TeV} \Rightarrow 20.3 \text{ fb}^{-1}$$

- CMS

$$\sqrt{s} = 7 \text{ TeV} \Rightarrow 5.1 \text{ fb}^{-1}$$

$$\sqrt{s} = 8 \text{ TeV} \Rightarrow 19.7 \text{ fb}^{-1}$$

Run 2 : May 2015 - ?

$$\sqrt{s} = 13 - 14 \text{ TeV}$$

The ATLAS Detector

A Toroidal Lhc ApparatuS

innermost layer

inner detector
extends to 1.2m, tracks charged particles using magnetic field, aims to identify location of vertex

solenoidal magnet

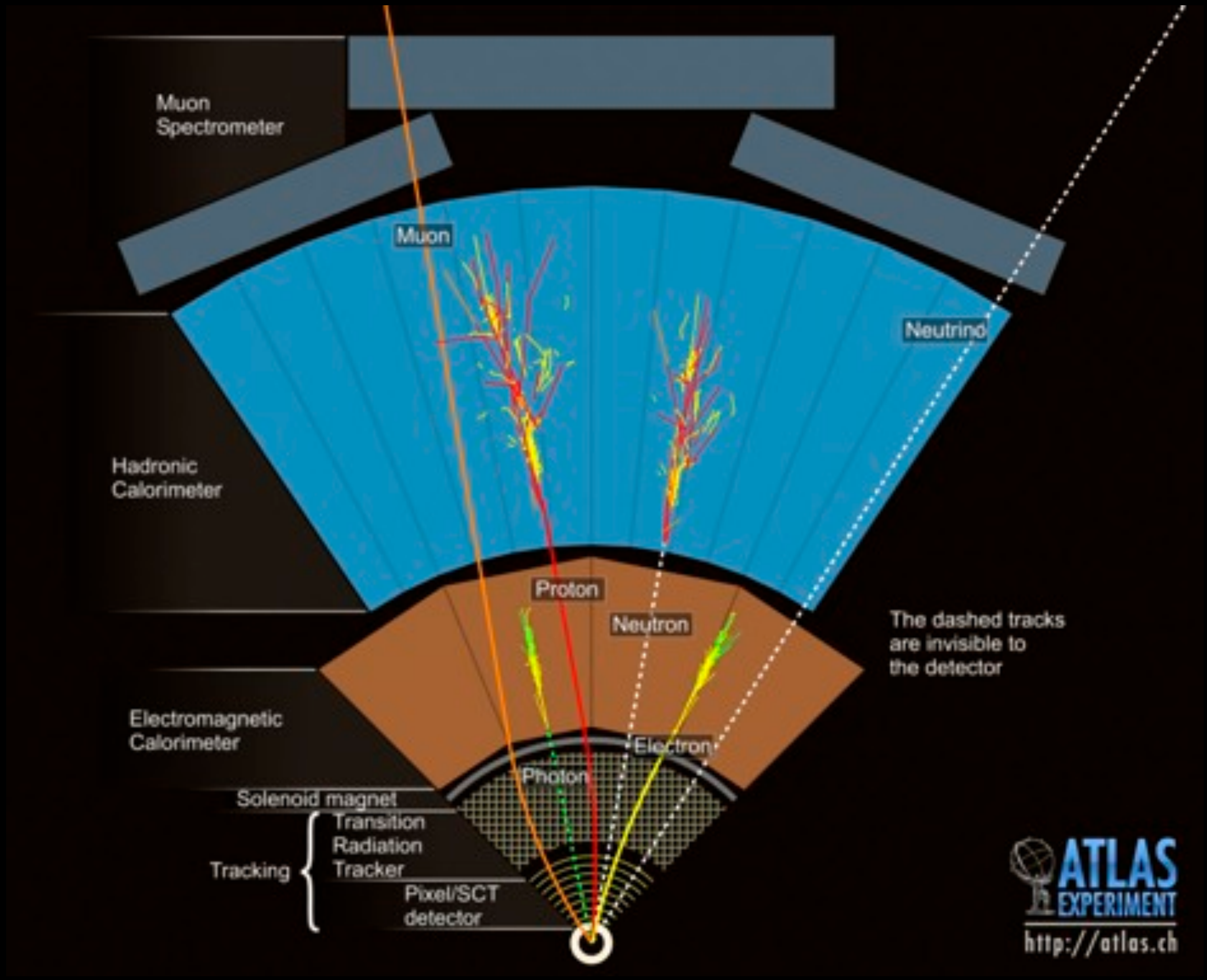
electromagnetic calorimeter
absorbs energy of EM particles with lead, samples path of particles with liquid argon

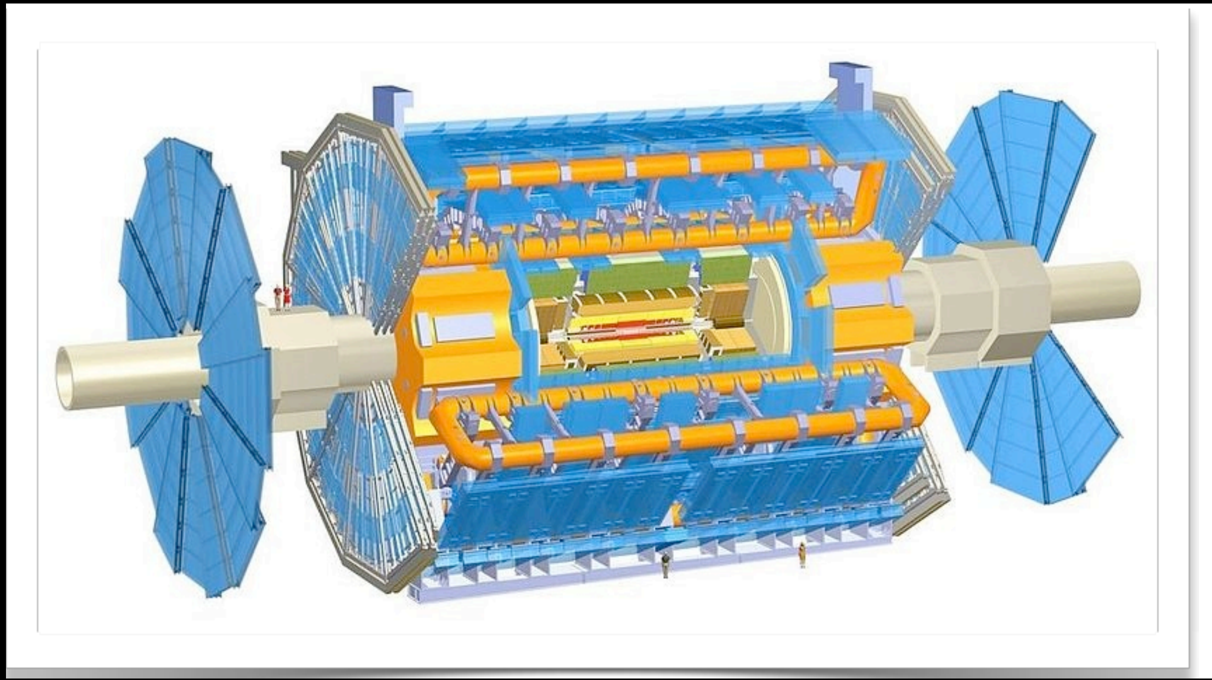
hadronic calorimeter
absorbs energy of strongly interacting particles with stainless steel. samples path of particles with liquid Ar, scintillators to track path

muon spectrometer
magnets curve the muons path

trigger system
selects 100 interesting events per second of 100 million events per second

outermost layer

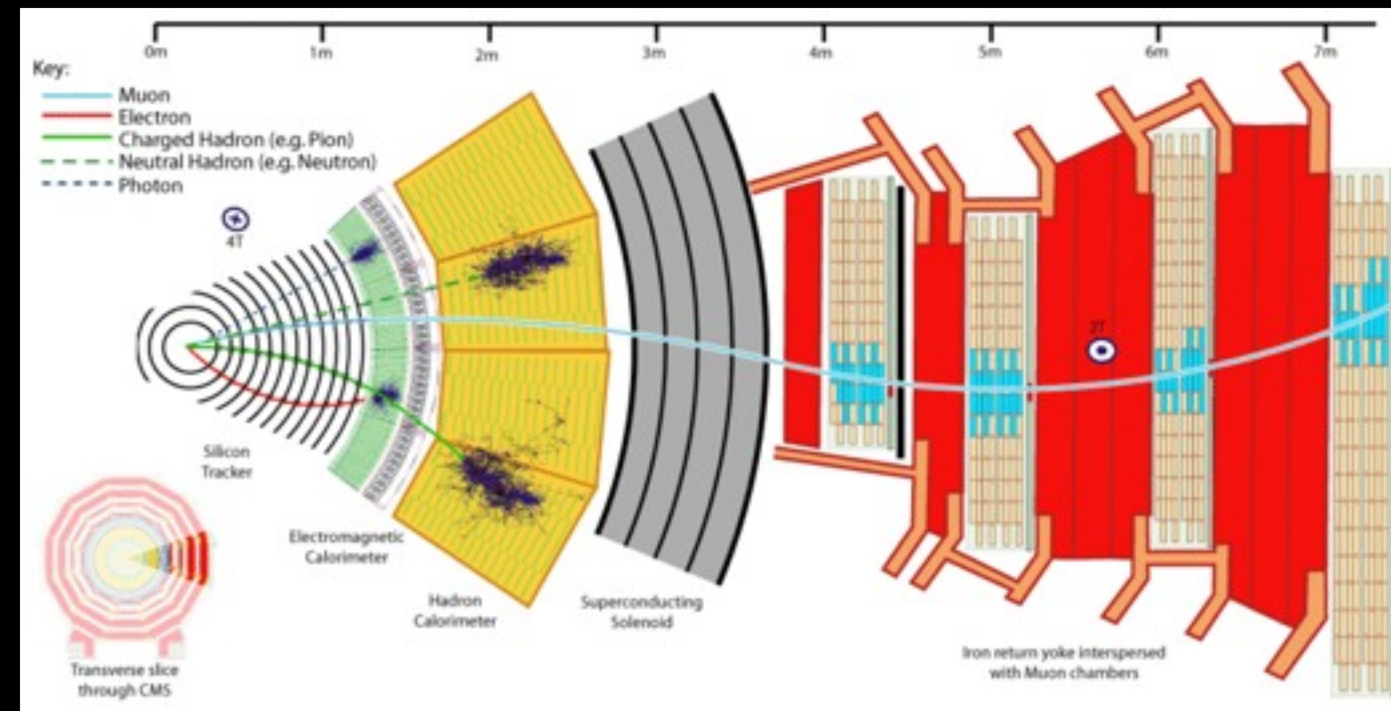




The CMS Detector

innermost layer

“Compact Muon Solenoid”



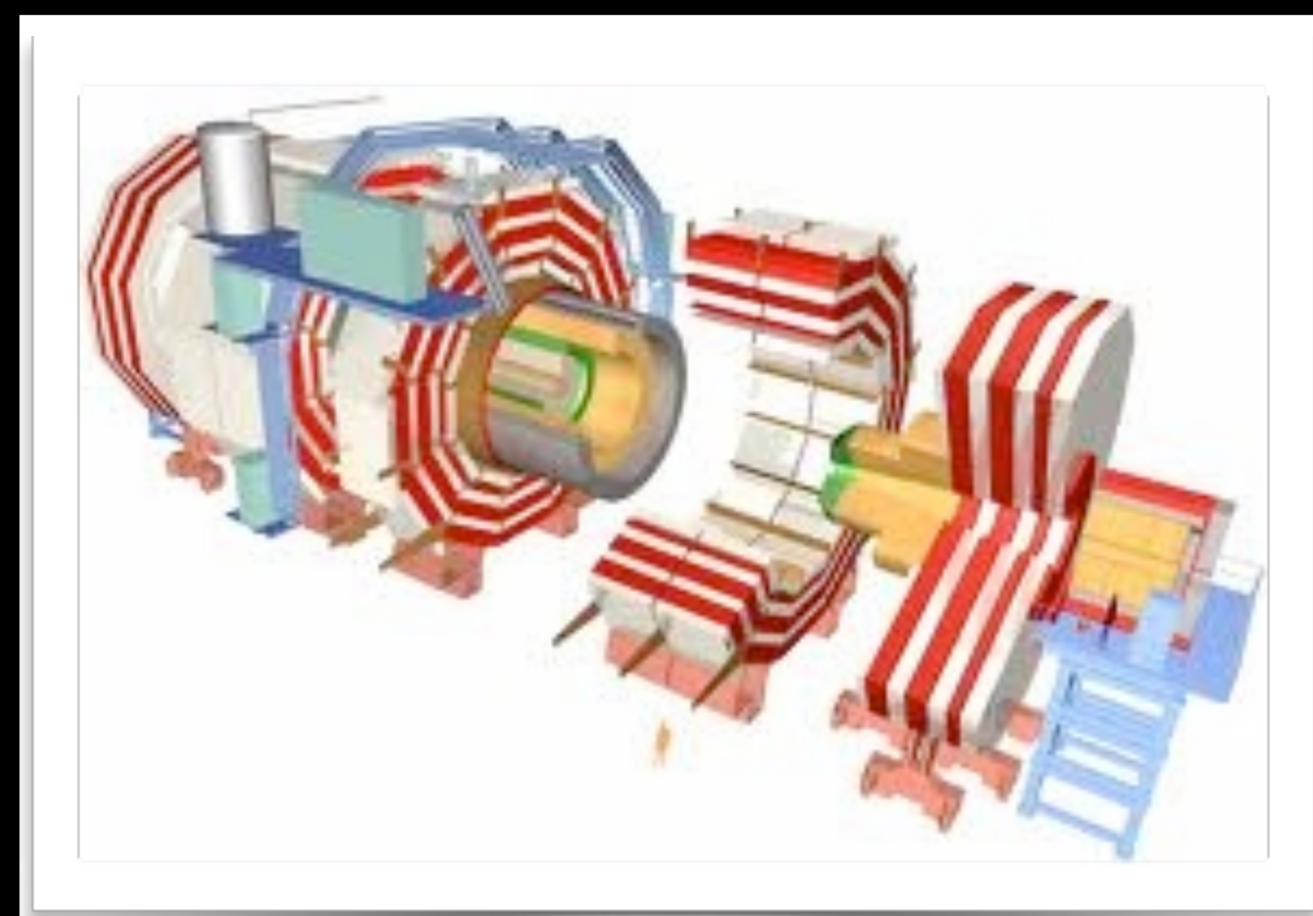
the tracker
extends to 1.1m, tracks charged particles using 9.6 million silicon strips

electromagnetic calorimeter
absorbs energy of EM particles with lead tungstate crystals

hadronic calorimeter
absorbs energy of strongly interacting particles with interspersed layers of brass/steel and plastic scintillators

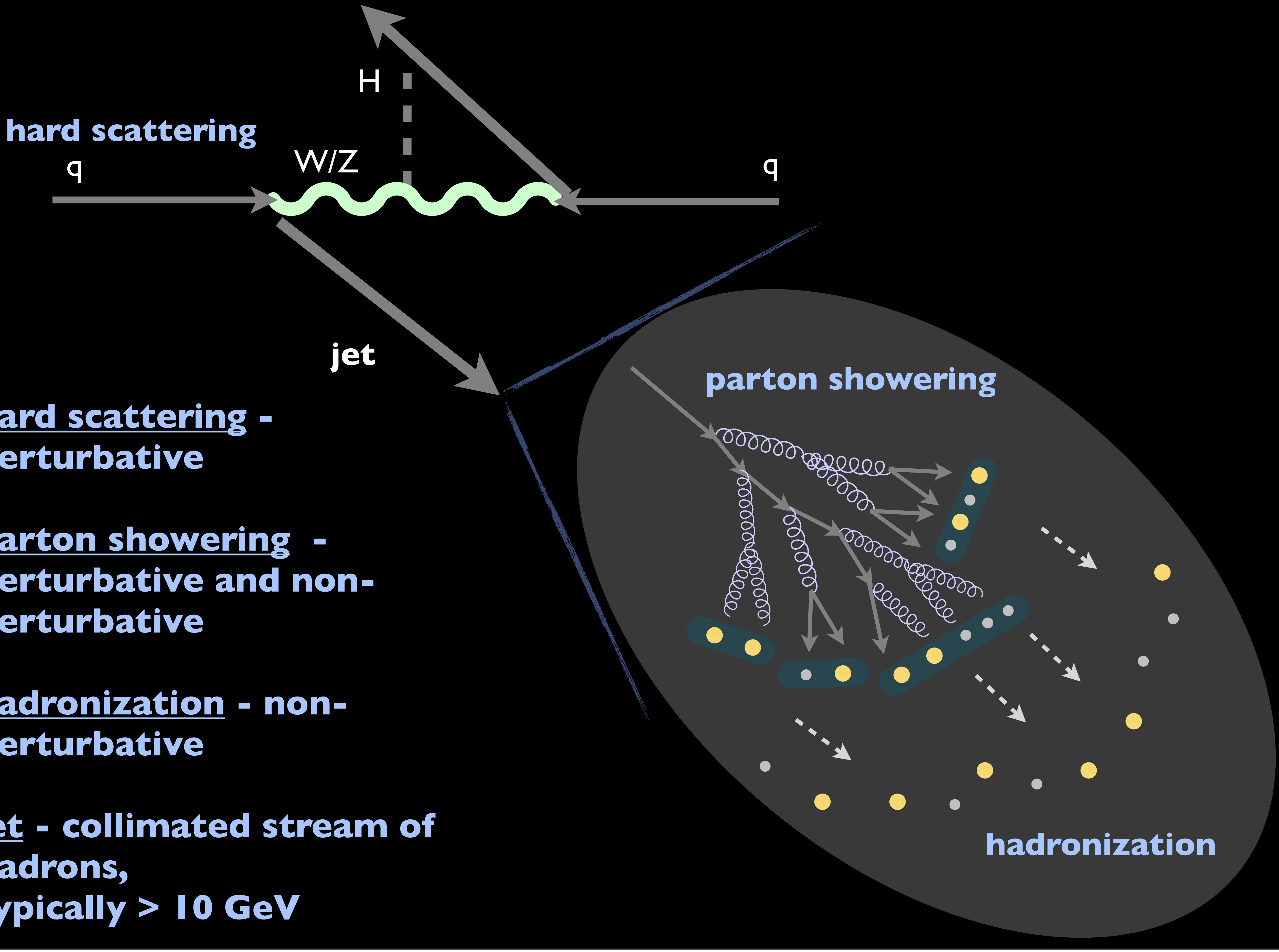
muon spectrometer
magnets curve the muons path

trigger system
select 100 interesting events per second from about 100 million events per second



outermost layer

Anatomy of an LHC Collision



hard scattering - perturbative

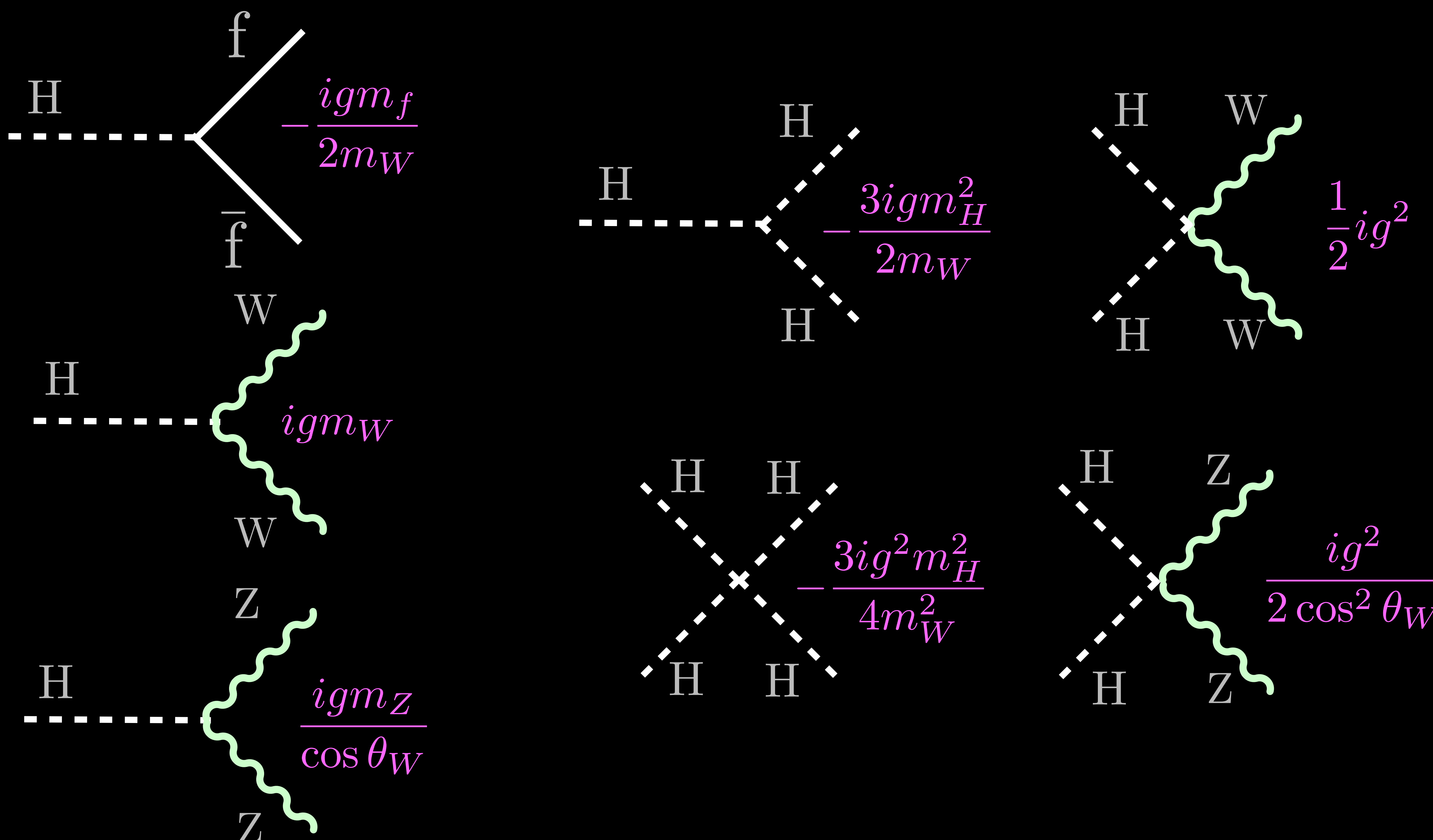
parton showering - perturbative and non-perturbative

hadronization - non-perturbative

jet - collimated stream of hadrons,
typically > 10 GeV

SM Higgs Interactions

once m_H is known, couplings can be measured and compared to SM prediction



possible LHC measurements

most likely impossible LHC measurements (ILC, ?)

SM Higgs Decay at the LHC

$H \to b\bar{b}$

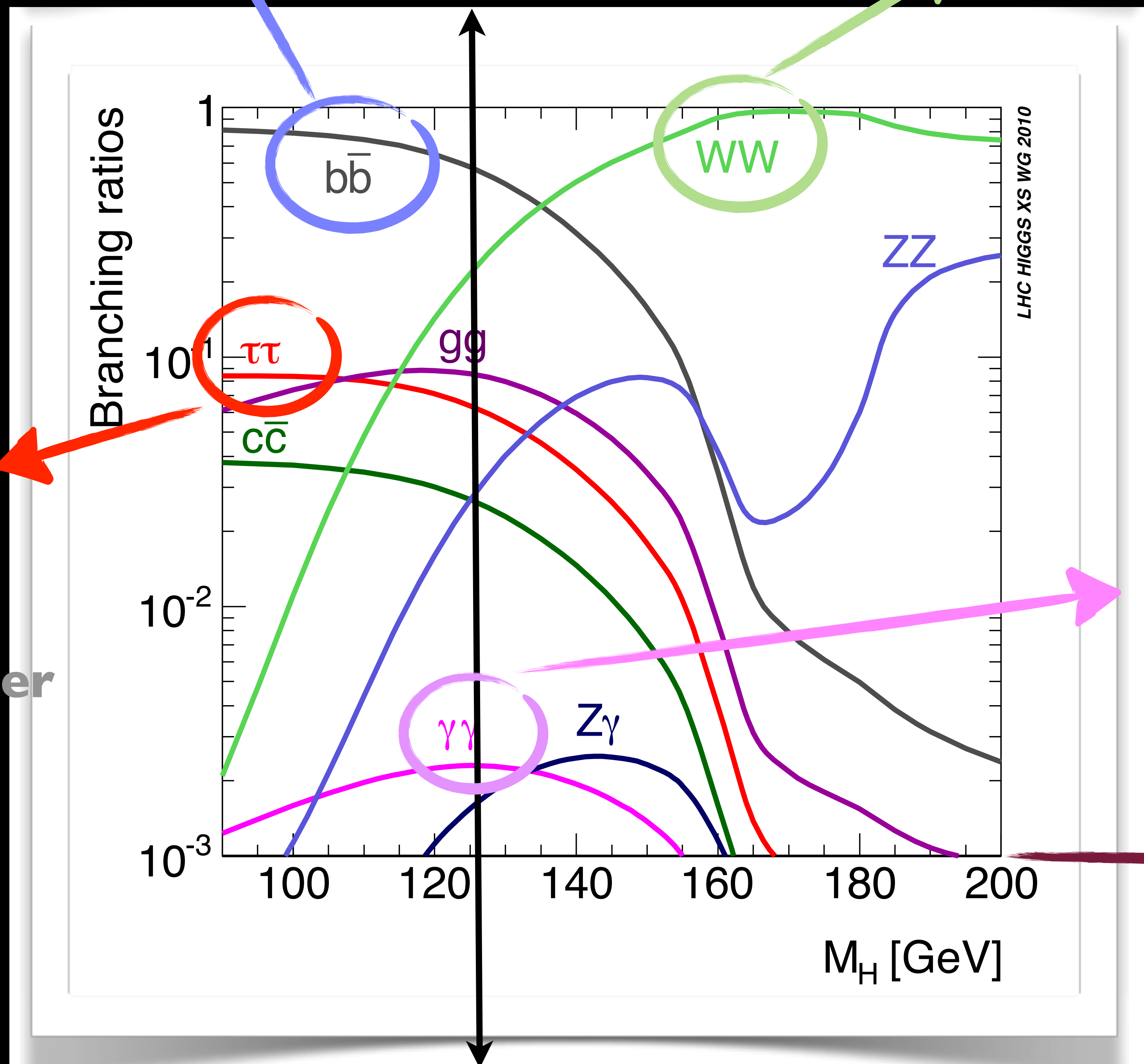
high decay rate, but b tagging efficiency at 60%

$WW \to l\nu l\nu$

clean and efficient, background under control

$\tau \to l\nu\nu$

clean and efficient, background under control

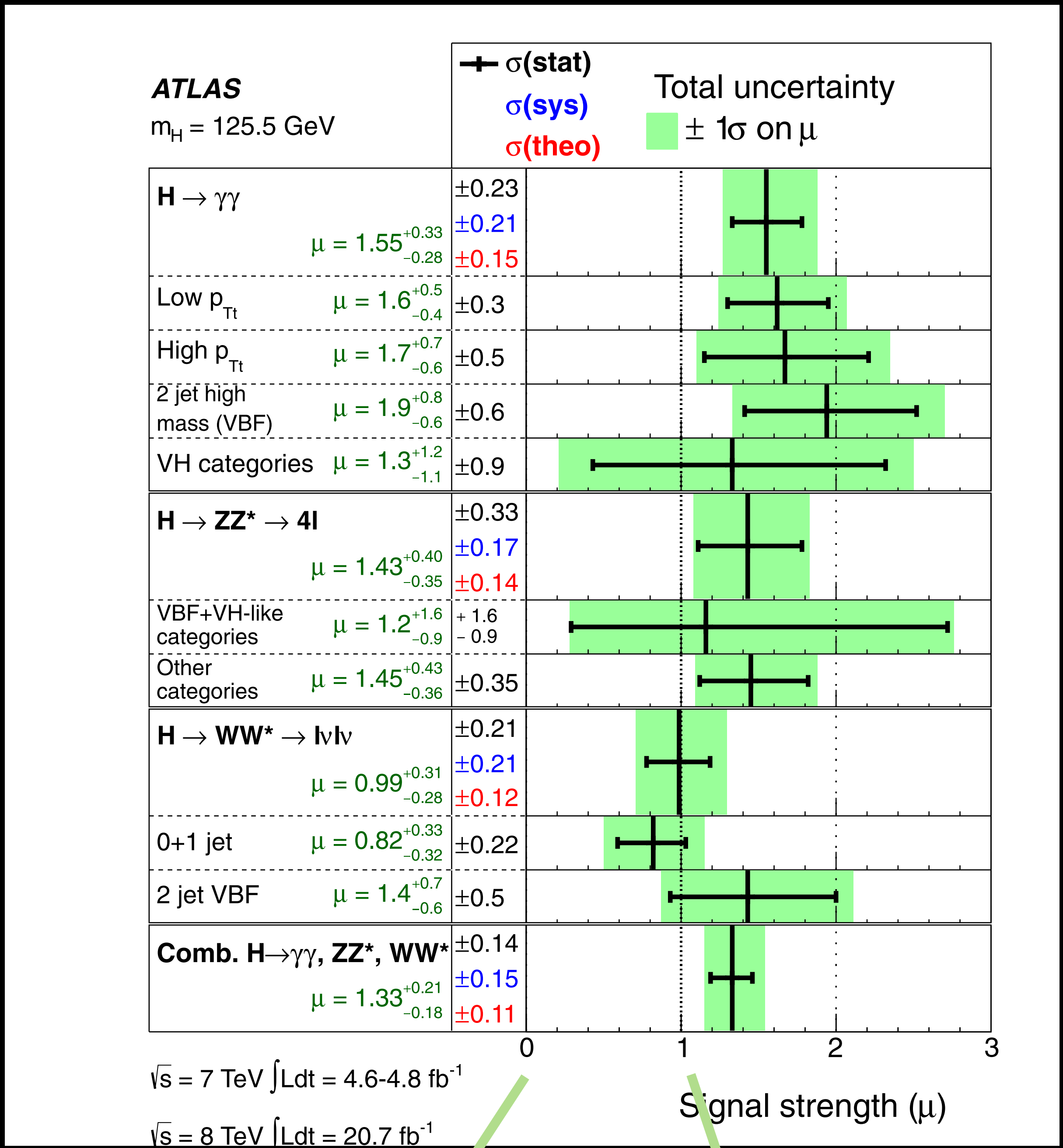


comparatively low rate, but very clean and efficient

$H \to t\bar{t}$

kicks in at 350 GeV

LHC Higgs-like Boson Discovery



$$\mu = 0$$

background only hypothesis

$$\mu = 1$$

SM Higgs boson hypothesis

combined mass measurement:

ATLAS:

$$m_H = 125.5 \pm 0.2(\mathrm{stat})^{+0.5}_{-0.6}(\mathrm{sys})\ \mathrm{GeV}$$

CMS:

$$m_H = 125.3 \pm 0.4(\mathrm{stat}) \pm 0.5(\mathrm{sys})\mathrm{GeV}$$

combined signal strength measurement:

ATLAS:

$$\mu = 1.33 \pm 0.14(\mathrm{stat}) \pm 0.15(\mathrm{sys})$$

CMS:

$$\hat{\mu} = \frac{\sigma}{\sigma_{\mathrm{SM}}} = 0.87 \pm 0.23$$

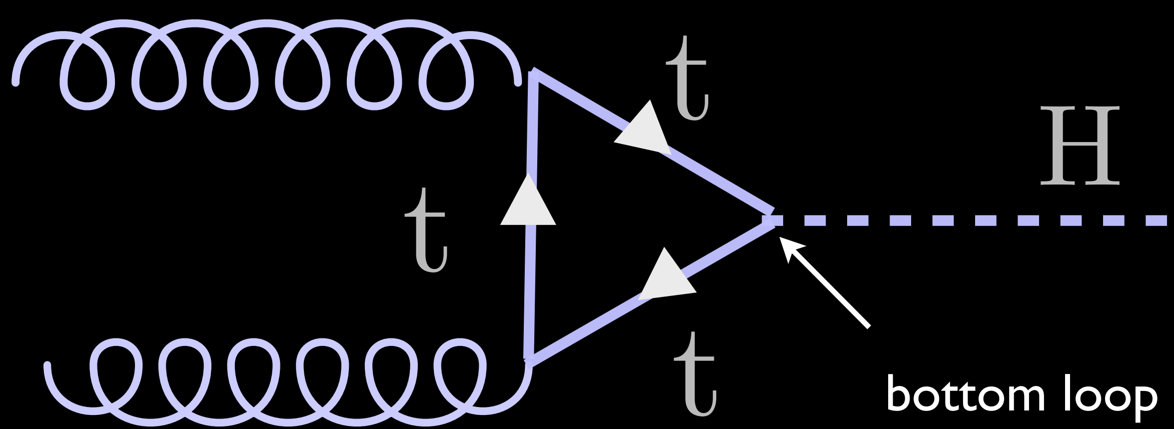
for M_H = 125 GeV

consistent with SM Higgs hypothesis

SM Higgs Production at the LHC

the gluon fusion channel - main LHC production mechanism

why?! more likely to find a gluon in the proton



bottom loop suppressed by ~ 0.1% - lighter quark loops even less likely

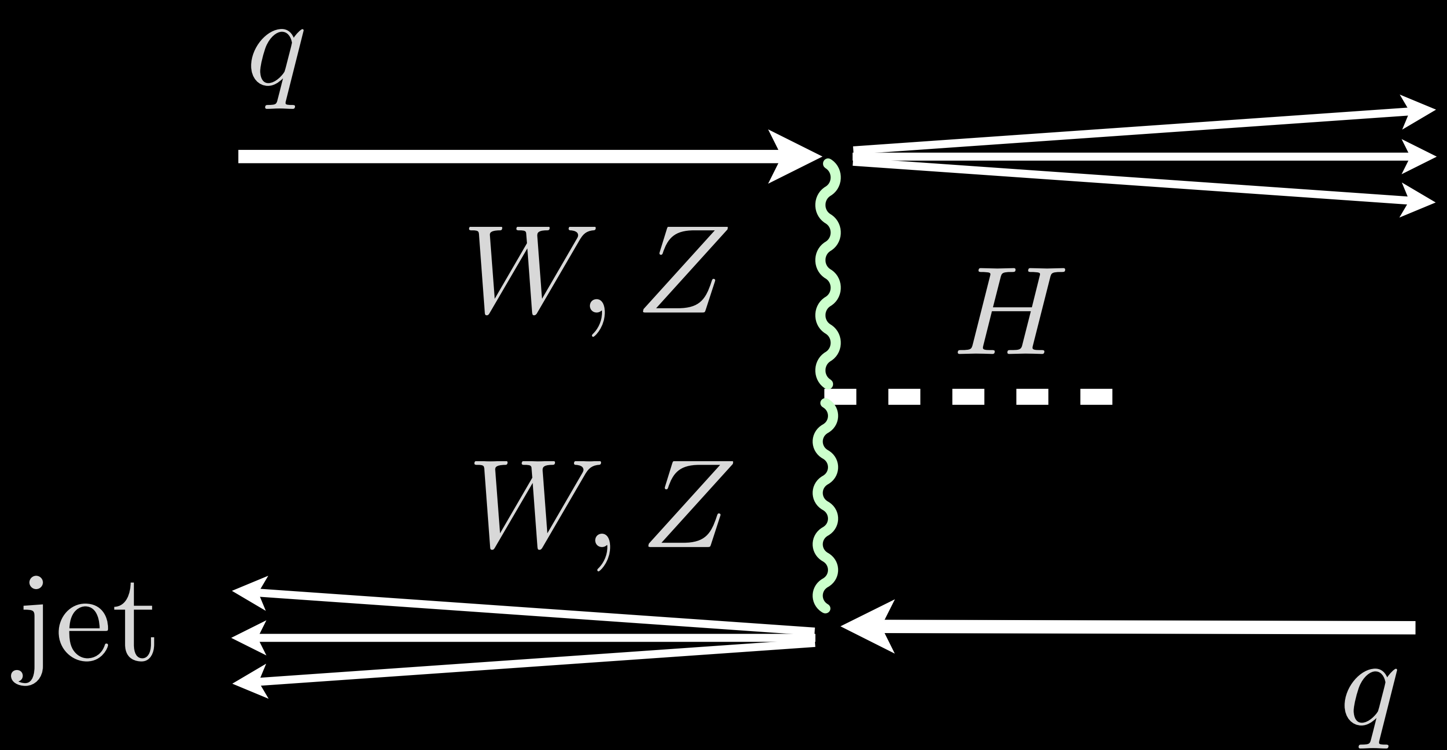
"gluon-gluon fusion" ggf

$$\sigma(gg \to H) \approx 15 \text{ pb at 7 TeV}$$

$$\sigma(gg \to H) \approx 50 \text{ pb at 14 TeV}$$

for $M_H = 125$ GeV

SM Higgs Production at the LHC



Vector Boson Fusion

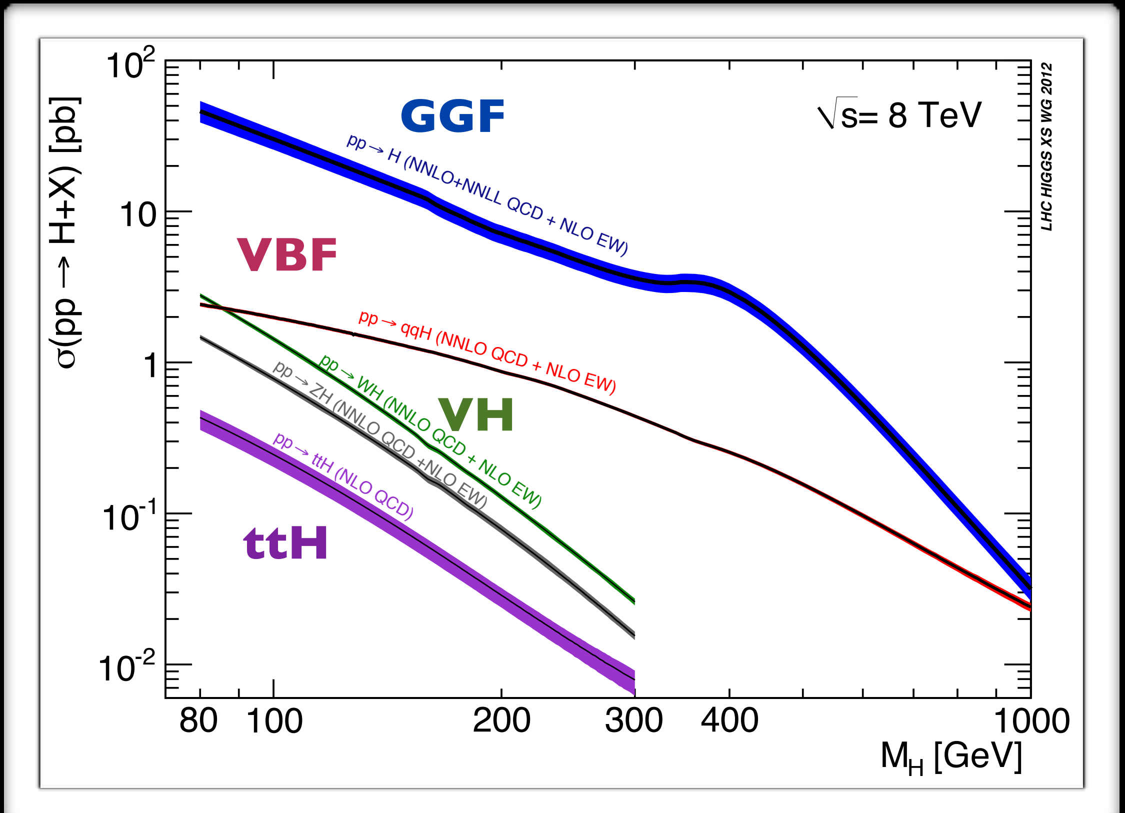
essential probe of EW higgs couplings - deviations from predicted rates could indicate BSM higgs physics

$$\sigma(qqH) \approx 1.3 \text{ pb at } 7 \text{ TeV}$$

$$\sigma(qqH) \approx 4 \text{ pb at } 14 \text{ TeV}$$

for $M_H = 125 \text{ GeV}$

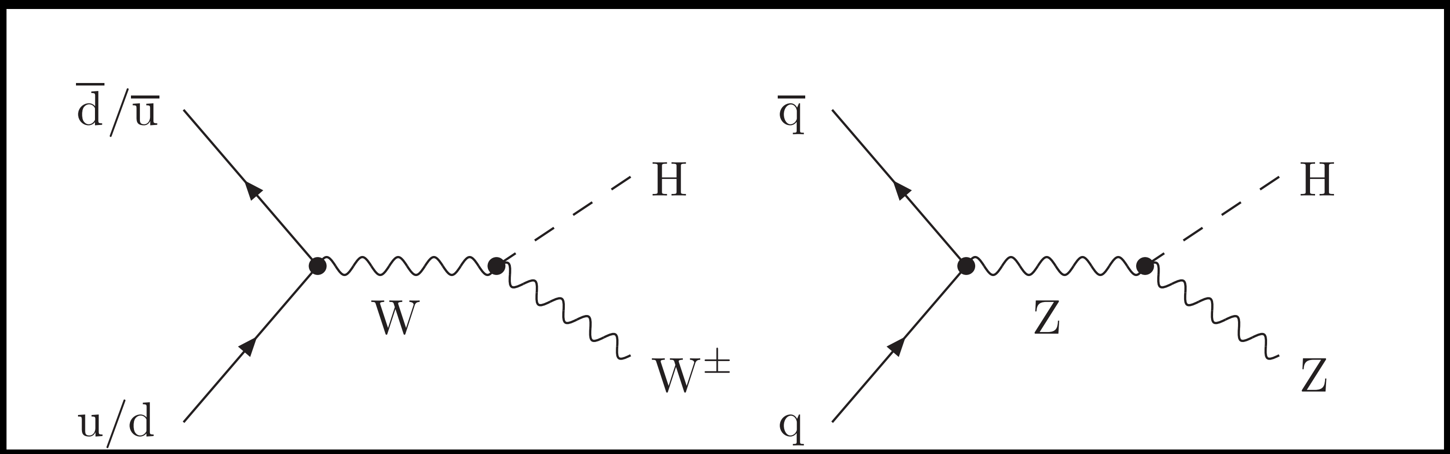
distinctive "forward - backward" jet topology unlike any background processes



lack of central jet activity - handle for discerning from backgrounds

SM Higgs Production at the LHC

the **Higgs-strahlung** channel

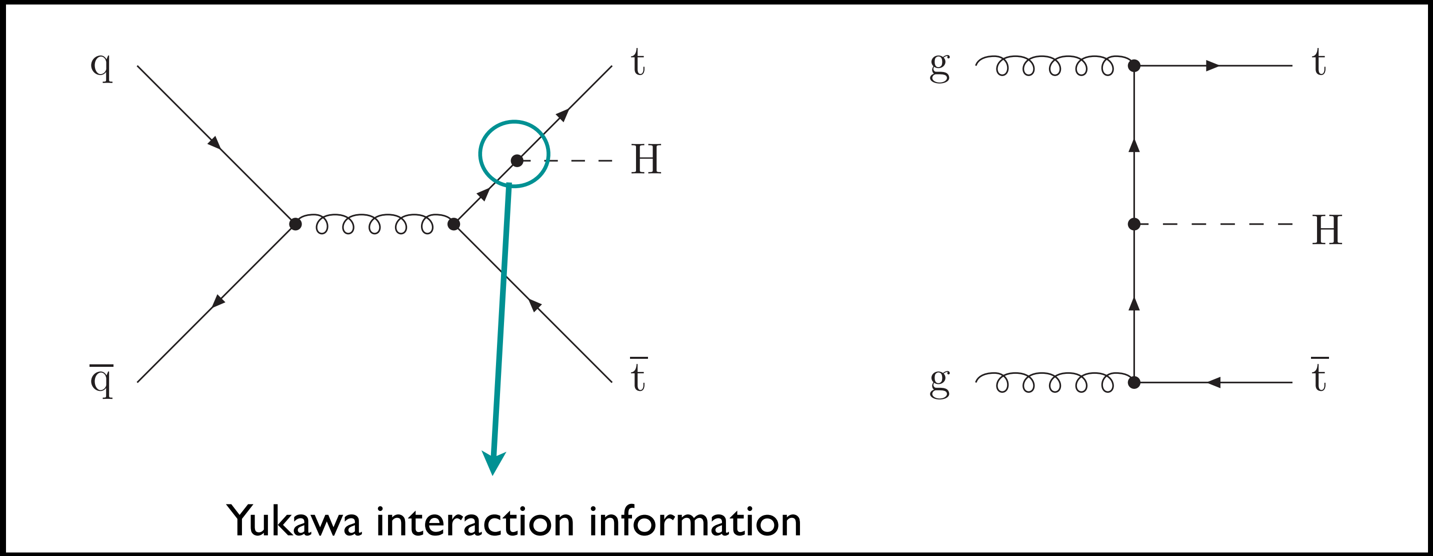


$$\sigma(W, ZH) \approx 0.6 \text{ pb at } 7 \text{ TeV}$$

$$\sigma(W, ZH) \approx 1.5 \text{ pb at } 14 \text{ TeV}$$

for $M_H = 125 \text{ GeV}$

the **ttH** channel - Higgs in association with a top quark



$$\sigma(t\bar{t}H) \approx 88 \text{ fb at } 7 \text{ TeV}$$

$$\sigma(t\bar{t}H) \approx 611 \text{ fb at } 14 \text{ TeV}$$

for $M_H = 125 \text{ GeV}$

The Fox-Wolfram Moments[1]

a rotationally invariant set of observables constructed from Legendre polynomials

$$H_\ell = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{s} P_\ell(\cos \Omega_{ij})$$

correlations between hadrons, jets, calorimeter entries...

weight factor

total angle between objects

$$\cos \Omega_{ij} = \cos \theta_i \cos \theta_j + \sin \theta_i \sin \theta_j \cos(\phi_i - \phi_j)$$

[1]Fox, Wolfram, PRL 1978

The Fox-Wolfram Moments

an event shape observable describing correlations between four-momentum objects

- **e+ e- to jets**

Fox, Wolfram Nucl. Phys. B 149 (1979) 413-496

- **Top Quark signal at Tevatron**

Field, Kanev, Tayebnejad PRD 55, 9 (1997)

- **B meson decays at Belle:**

Toru Iijima, hep-ex 0105005 (2001)

- **``Fox-Wolfram Moments in Higgs Physics´´**

C.B., Buschmann, Butter, Plehn PRD 87, 073014 (2013)

- **``Improving Higgs plus Jets analyses through Fox-Wolfram Moments´´**

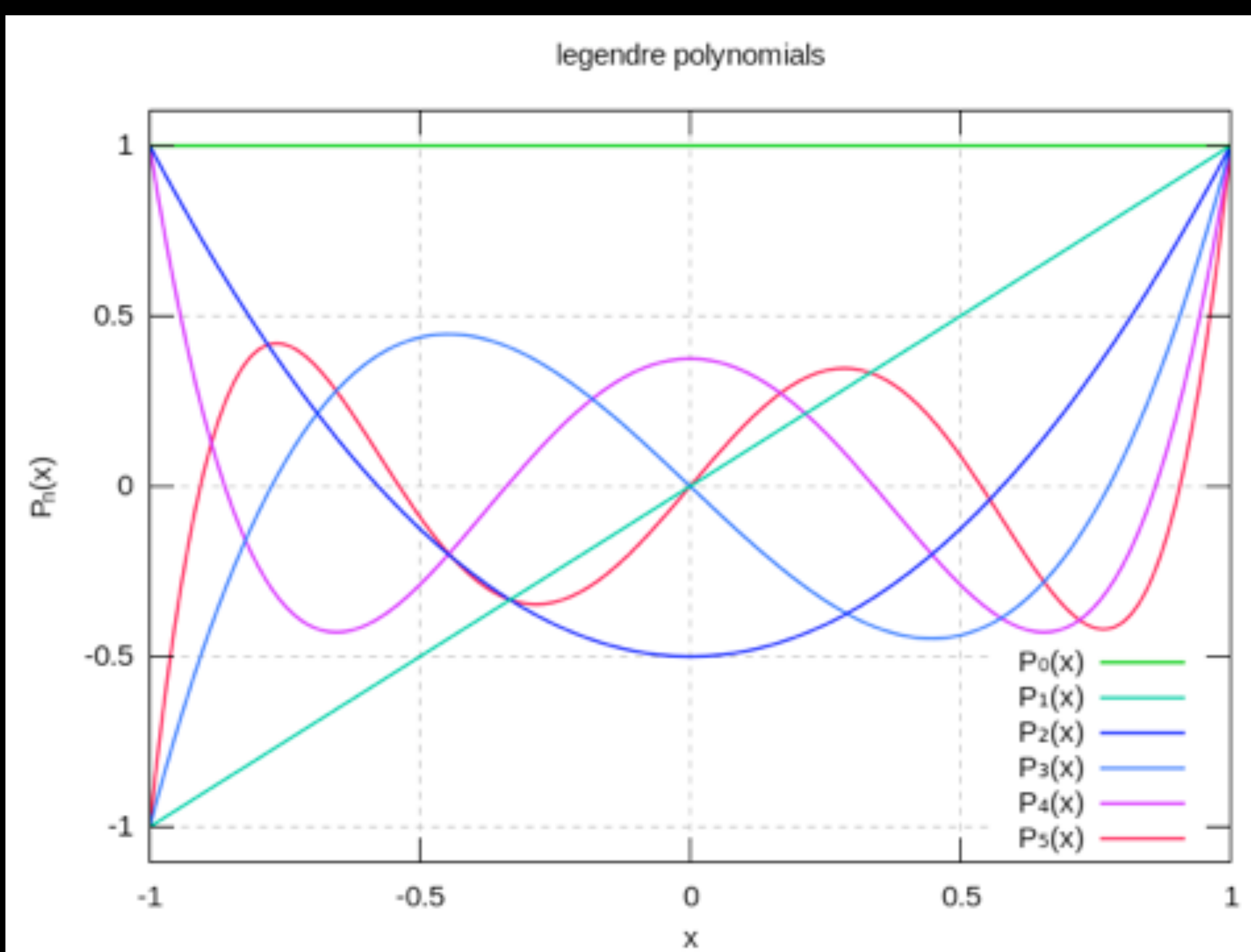
C.B., Mellado, Plehn, Ruan, Schichtel, PRD 89, 053006 (2014)

Legendre Polynomials

occur as series solution to Laplace's equation in spherical coordinates

$$\frac{d}{dx}\left[(1-x^2)\frac{d}{dx}P_n(x)\right]+n(n+1)P_n(x)=0$$

$$P_n(x)=\frac{1}{2^n n!}\frac{d^n}{dx^n}\left[(x^2-1)^n\right]$$



$$P_0(x)=1\,,\;P_1(x)=x$$

$$P_2(x)=\frac{1}{2}(3x^2-1)$$

$$P_3(x)=\frac{1}{2}(5x^3-3x)$$

$$\vdots$$

$$P_7(x)=\frac{1}{16}(429x^7-693x^5+315x^3-35x)$$

The Fox-Wolfram Moments

$$H_\ell = \sum_{i,j} \frac{|\vec{p}_i||\vec{p}_j|}{s} P_\ell(\cos\Omega_{ij})$$

"weight factor"

$$0 \leq H_\ell \leq 1$$

$$W_{ij}^T = \frac{p_{Ti}p_{Tj}}{p_{T,\mathrm{tot}}^2} \qquad W_{ij}^U = 1 \qquad W_{ij}^p = \frac{|\vec{p}_i||\vec{p}_j|}{|\vec{p}|_{\mathrm{tot}}^2}$$

transverse momentum weight

unit weight

magnitude momentum weight

Fox-Wolfram Moments - 2 jet properties

$$H_\ell = \sum_{i,j=1}^{2} \frac{W_i W_j}{W_{\text{tot}}^2} P_\ell(\cos\Omega_{ij})$$

$$= \frac{1}{(W_1 + W_2)^2} \big[W_1^2 P_\ell(\cos 0) + W_2^2 P_\ell(\cos 0)$$

$$+ W_1 W_2 P_\ell(\cos\Omega_{12}) \big]$$

$$= 1 + \frac{2W_1 W_2}{(W_1 + W_2)^2} P_\ell(\cos\Omega_{12})$$

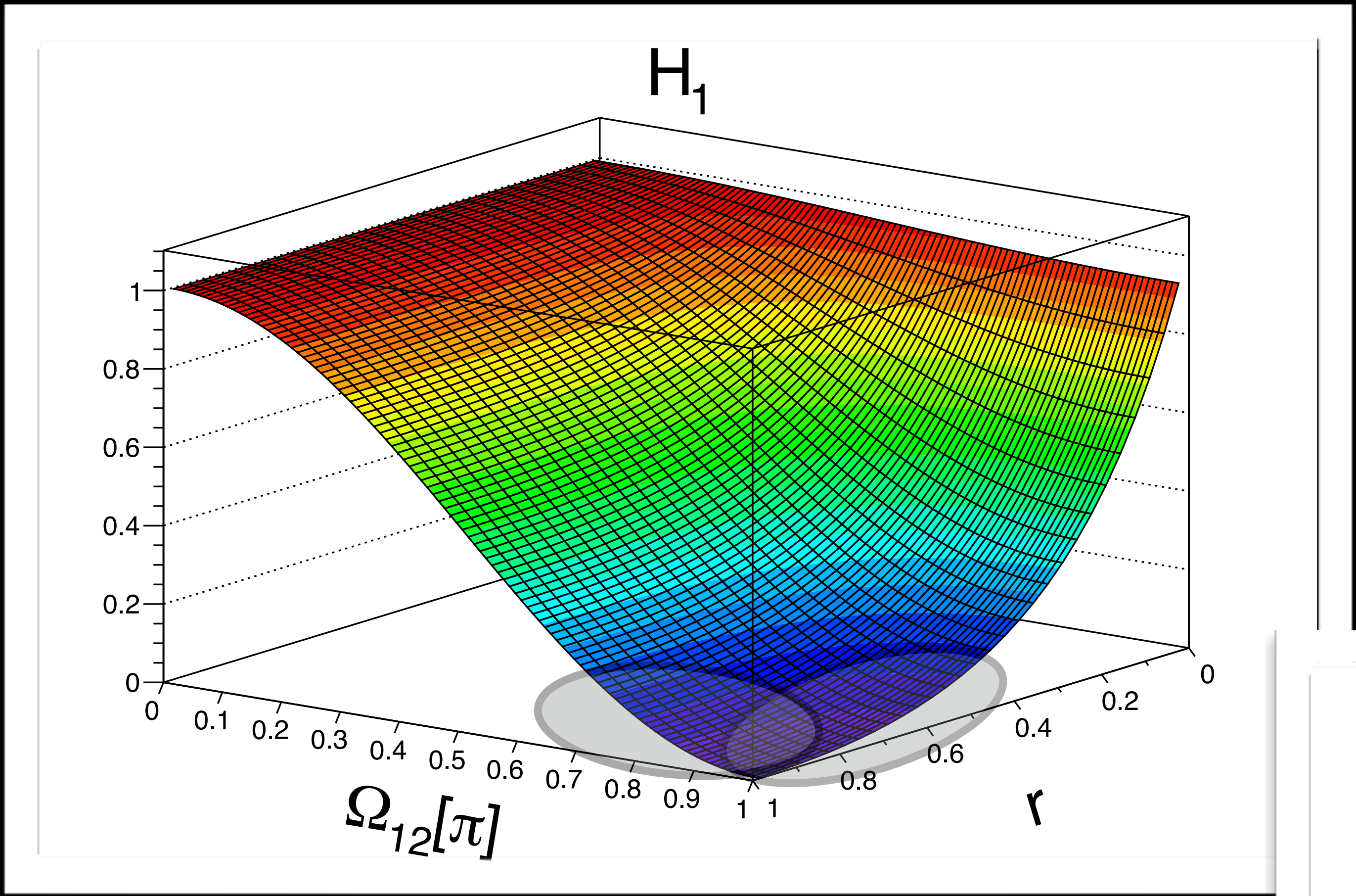
$$= \frac{1 + 2r P_\ell(\cos\Omega_{12})}{1 + 2r + r^2}$$

$$r = \frac{W_2}{W_1}$$

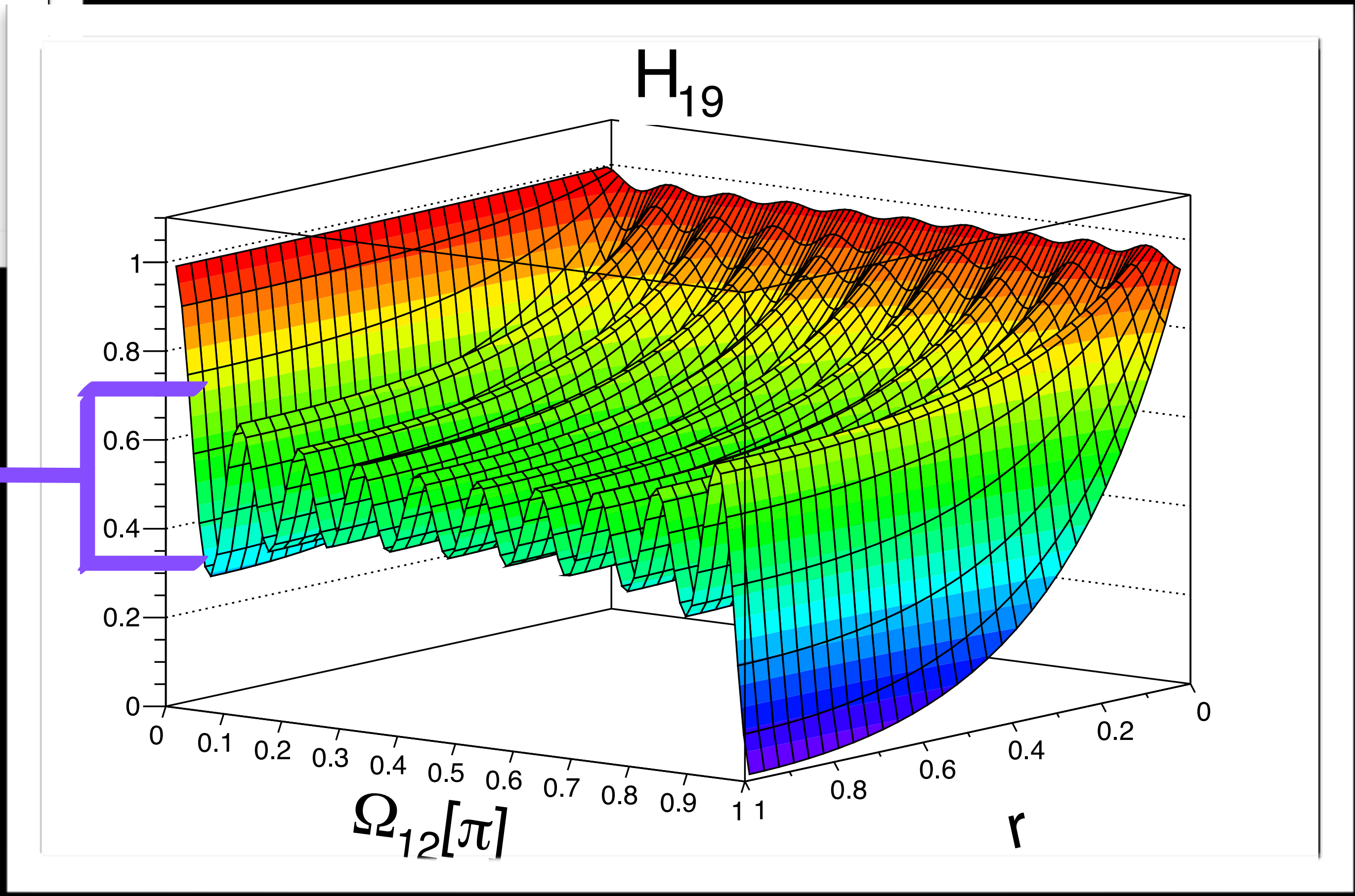
$$0 \le r \le 1$$

Fox-Wolfram moments - 2 jet properties

odd moments - best for discriminating back-to-back jets, higher moments resolve larger angular j_1 j_2 separation



$$r = \frac{W_2}{W_1}$$



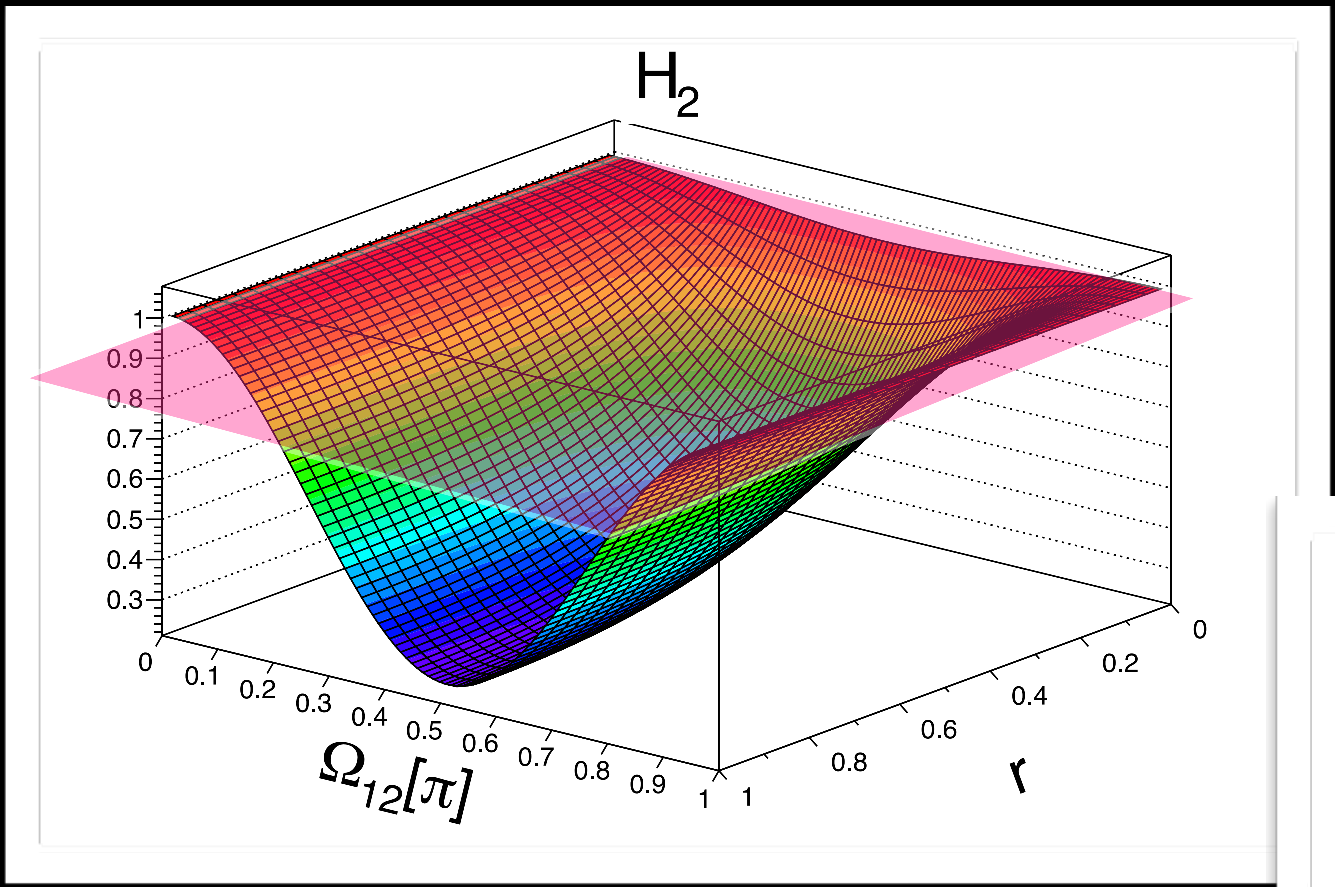
multivalued function, no resolution to intermediate values of Ω_{12}

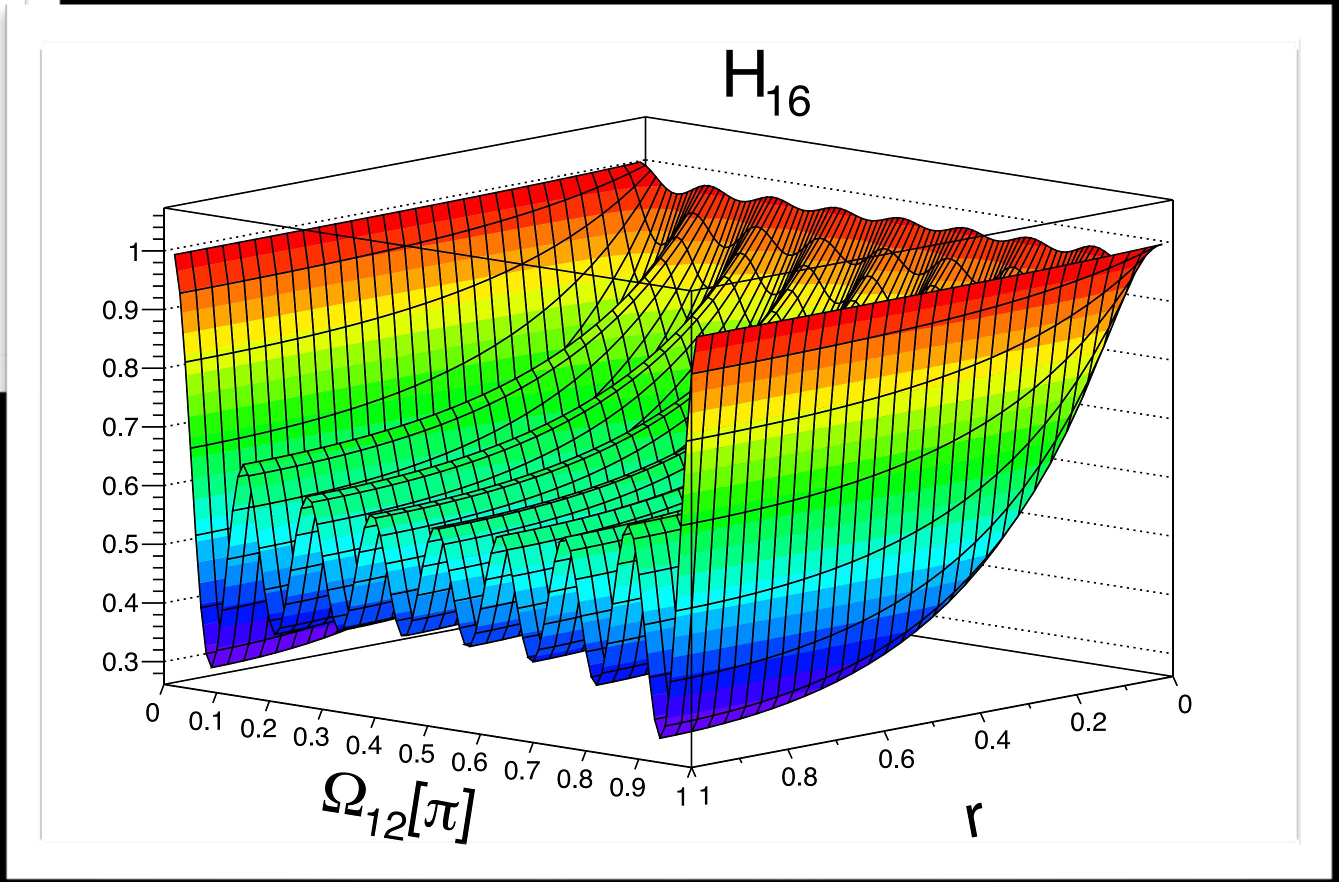
$$H_\ell \to 0 \quad \text{for} \quad \Omega_{12} \to \pi$$

Fox-Wolfram moments - 2 jet properties

even moments - symmetry of even function reduces discriminatory power

$$H_\ell \to 1 \quad \text{for} \quad \Omega_{12} \to 0 \quad \text{AND} \quad \Omega_{12} \to \pi$$



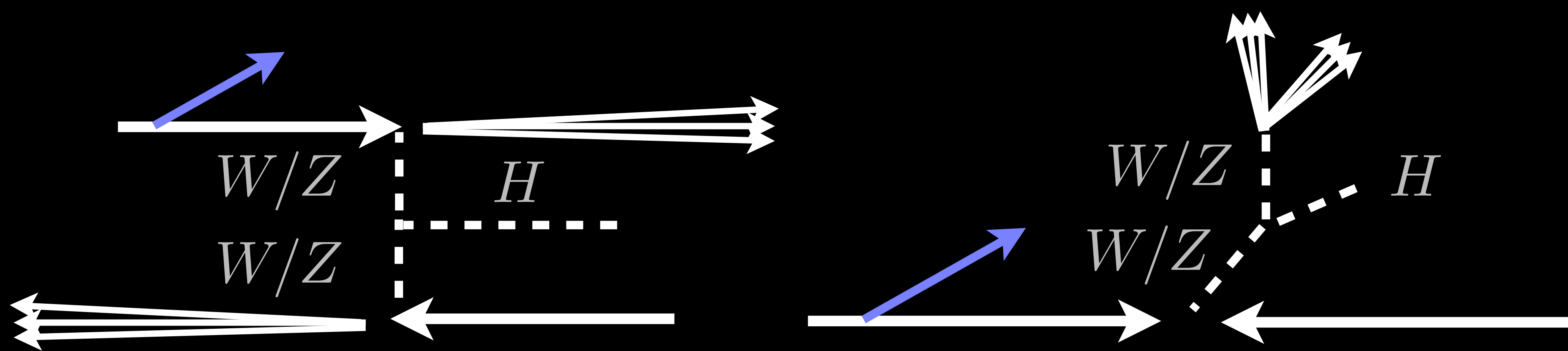


low, even moments may discern non forward-backward jets

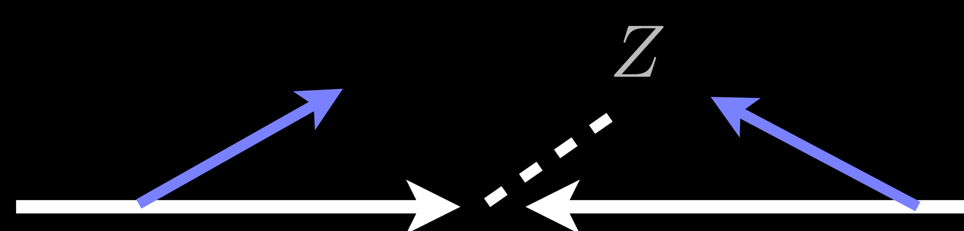
Analysis for H --> tau tau

(process + hard jet) x PS with CKKW using SHERPA

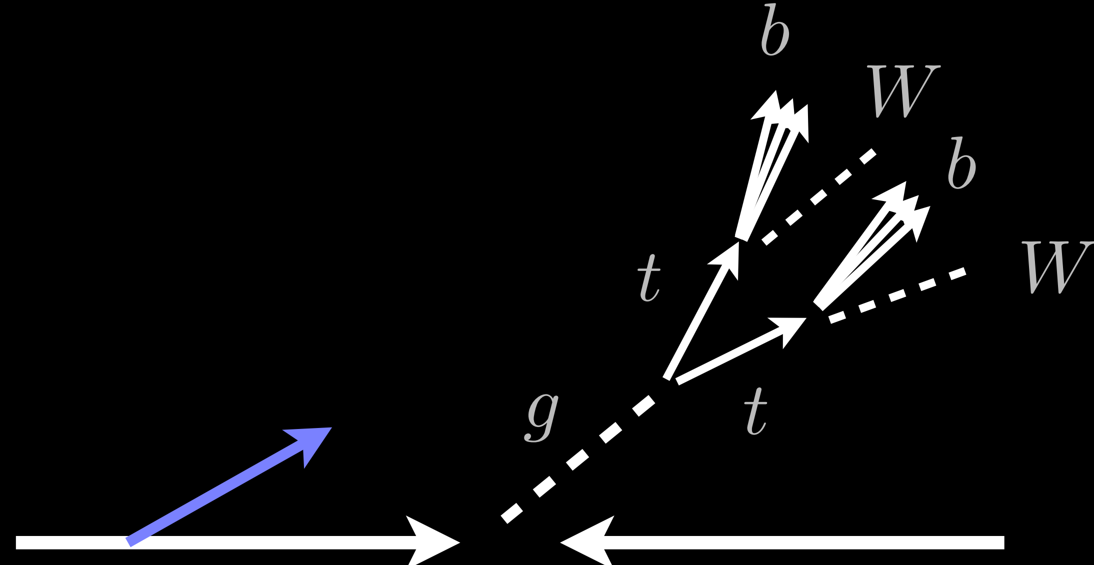
signal WBF



background QCD ZJJ



background Top Pair



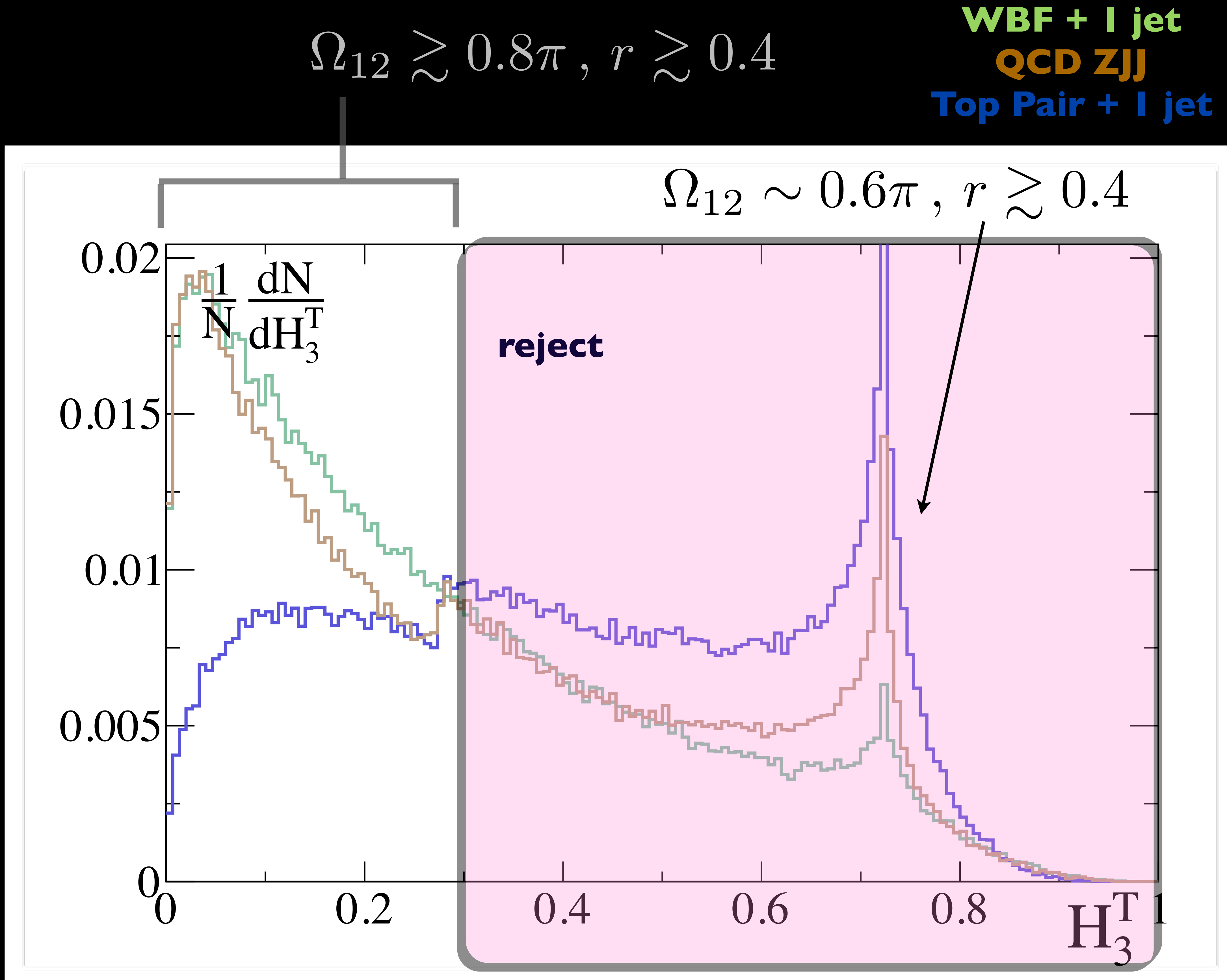
Fastjet anti-kT algorithm with R = 0.4, 8TeV

Cutflow Analysis

acceptance	WBF + 1 jet % fail	WBF + 1 jet XS (fb)	QCD ZJJ % fail	QCD ZJJ XS (fb)	Top Pair % fail	Top Pair XS (fb)	S / B
		18.7		115000		17200	1/7070
$p_{T j_1, j_2} > 20$ GeV	29.4	13.2	93.2	7820	9.63	15500	1/1767
$\|y_{j_1, j_2}\| < 5.0$	1.49	13.0	0.97	7740	0.182	15500	1/1788
$\Delta R_{j_1 j_2} > 0.7$	2.73	12.6	3.84	7440	2.32	15100	1/1789
$m_{j_1 j_2} > 600$ GeV	68.9	3.92	96.6	253	95.8	634	1/226
$b - veto$	NA	3.92	NA	253	54.0	292	1/139
$y_1 \cdot y_2 < 0$	1.41	3.86	9.17	230	13.8	252	1/125
$\|y_{j_1} - y_{j_2}\| > 4.4$	13.9	3.32	31.8	157	66.1	85.4	1/73

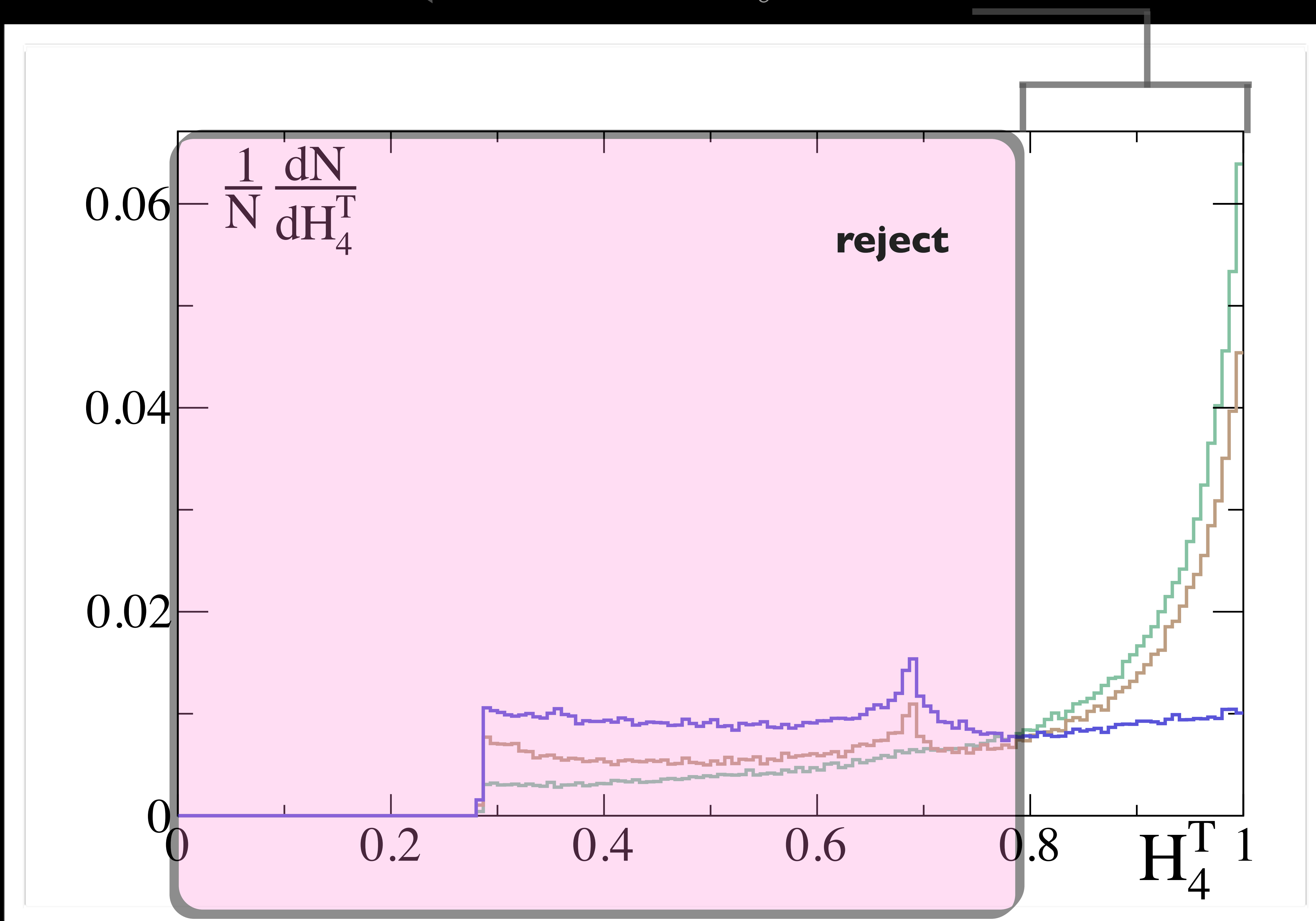
can cuts on FWM replace or be added to current cuts used for VBF event selection?

Cuts on FWM Distributions



Cuts on FWM Distributions

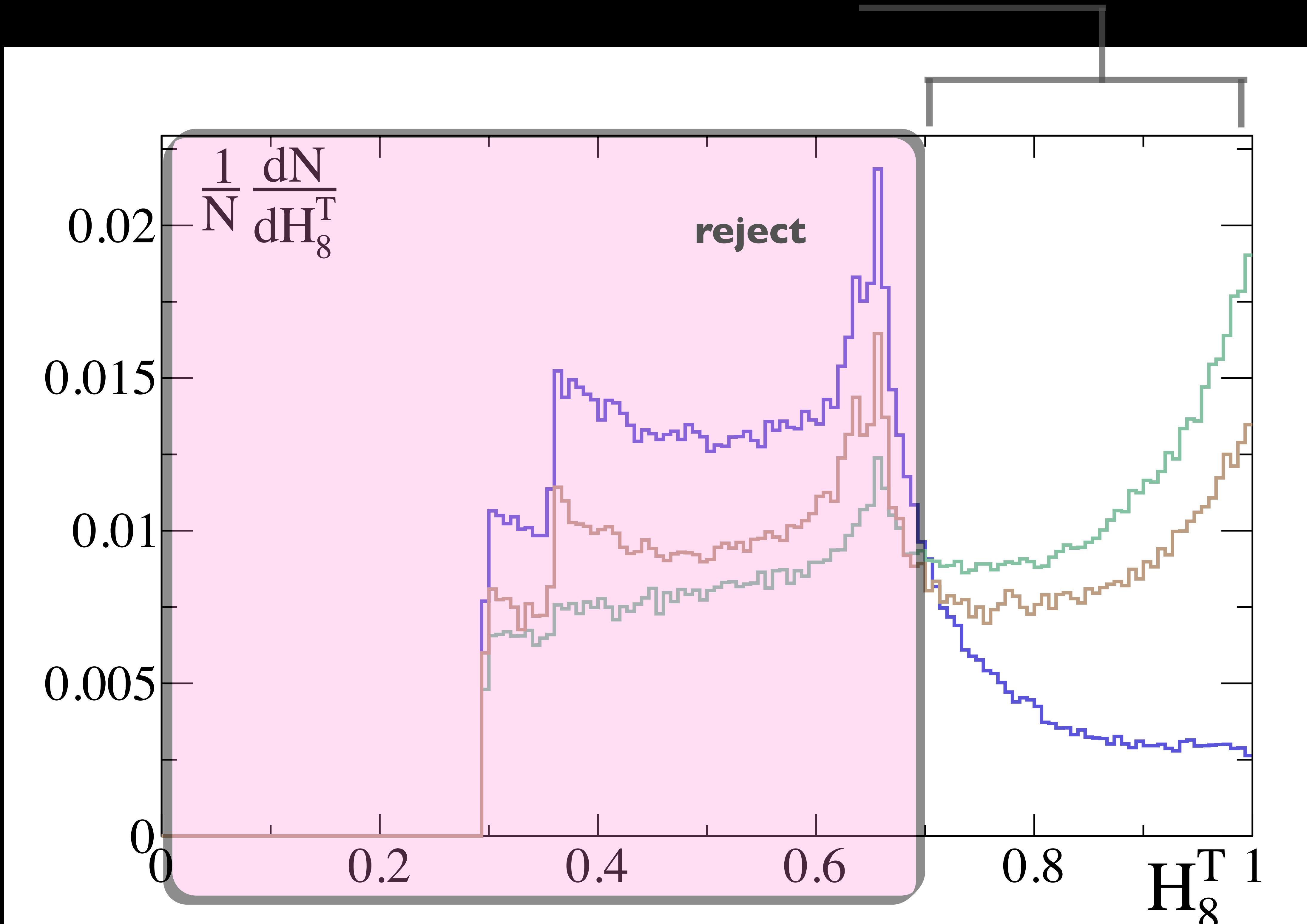
OR
$\Omega_{12} \sim 0, \pi \quad \text{any } r$
$r \leq 0.3 \quad \text{any } \Omega_{12}$



Cuts on FWM Distributions

OR
$\Omega_{12} \sim 0, \pi \quad \text{any } r$
$r \leq 0.3 \quad \text{any } \Omega_{12}$

WBF + 1 jet
QCD ZJJ
Top Pair + 1 jet



Cuts on FWM Distributions[1]

acceptance	WBF + 1 jet		QCD ZJJ		Top Pair		S / B
	% fail	XS (fb)	% fail	XS (fb)	% fail	XS (fb)	
min cuts + b-veto		3.92		253		292	1/139
$H_3^T < 0.3$	38.4	2.41	44.4	141	64.6	103	1/101
$H_4^T > 0.8$	35.8	2.52	48.1	131	73.3	78.0	1/83
$H_8^T > 0.8$	50.1	1.96	60.5	100	81.6	53.7	1/78
$H_{12}^T > 0.7$	64.5	1.39	73.0	68.3	88.0	35.0	1/74
rapidity gap	13.9	3.32	31.8	157	66.1	85.4	1/73

[1]C.B. et.al, PRD 87, 073014 (2013)

Analysis - Cutting on FWM

after typical WBF cuts are exhausted, can the moments help?

acceptance	WBF + 1 jet		QCD ZJJ		Top Pair		S / B
	% fail	XS (fb)	% fail	XS (fb)	% fail	XS (fb)	
		18.7		115000		17200	1/7070
minimal cuts + b veto	NA	3.92	NA	253	54.0	292	1/139
central jet cuts	13.9	3.32	31.8	157	66.1	85.4	1/73

$H_{12}^T > 0.7$ 1/57

top pair background can be further supressed based on tagging jet correlations rephrased ito FWM

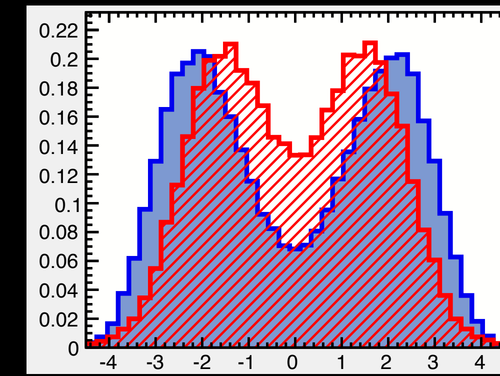
Classification Rule

A "classifier" is a rule for determining which <u>class</u> an <u>instance</u> of a <u>set</u> belongs to

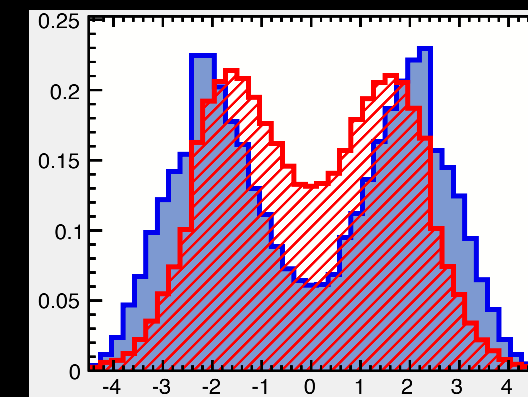
class → sig/bkg   instance → event   set → data or MC sample

instance	y_{j_1}	y_{j_2}	Δy_{12}	m_{12}	class
event 1	2.79854	-1.33015	4.12869	264.056 GeV	S
event 2	1.5059	-1.09764	2.60354	156.285 GeV	B
⋮	⋮	⋮	⋮	⋮	⋮
event n	-1.10029	1.83929	2.93958	209.104 GeV	S

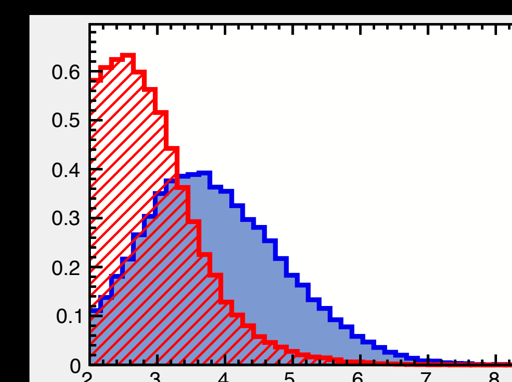
$y(\vec{x}) \in \mathbb{R}$ map all information of an event onto a real number - the "scalar output" of the classifier



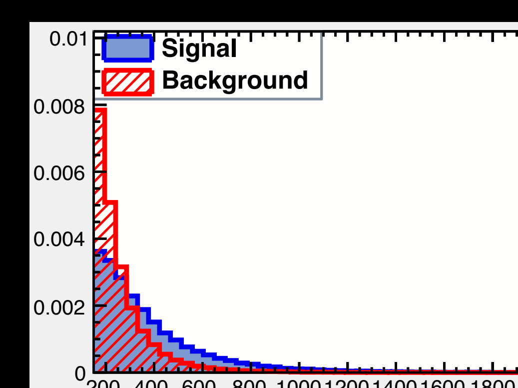
y_{j_1}



y_{j_2}



Δy_{12}



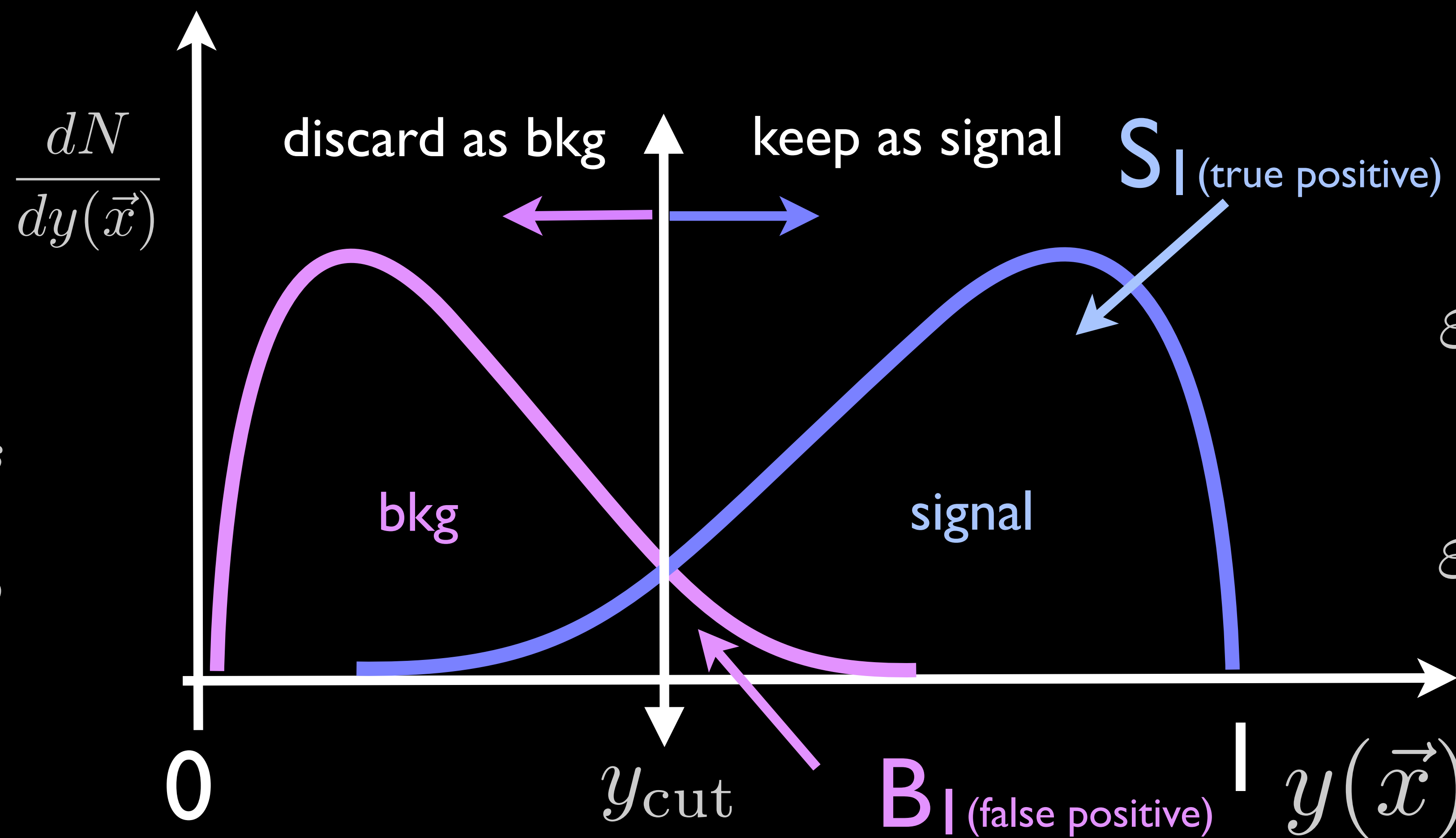
m_{12}

Classification Response and ROC Curves

rejection:
discard events

$$r_s = 1 - \varepsilon_s$$

$$r_b = 1 - \varepsilon_b$$



efficiency:
keep events

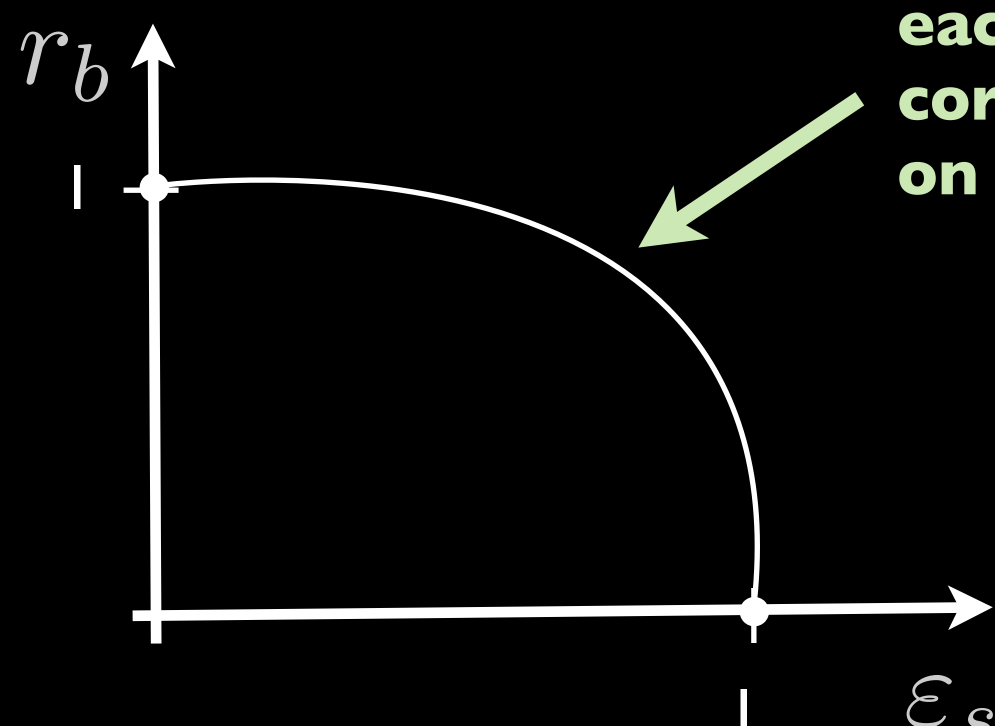
$$\varepsilon_s = \frac{S_1}{S_{tot}}$$

$$\varepsilon_b = \frac{B_1}{B_{tot}}$$

if $y_{cut} = 1$

$$(\varepsilon_s, r_b) = (0, 1)$$

ROC curve
(Receiver Operating
Characteristic)



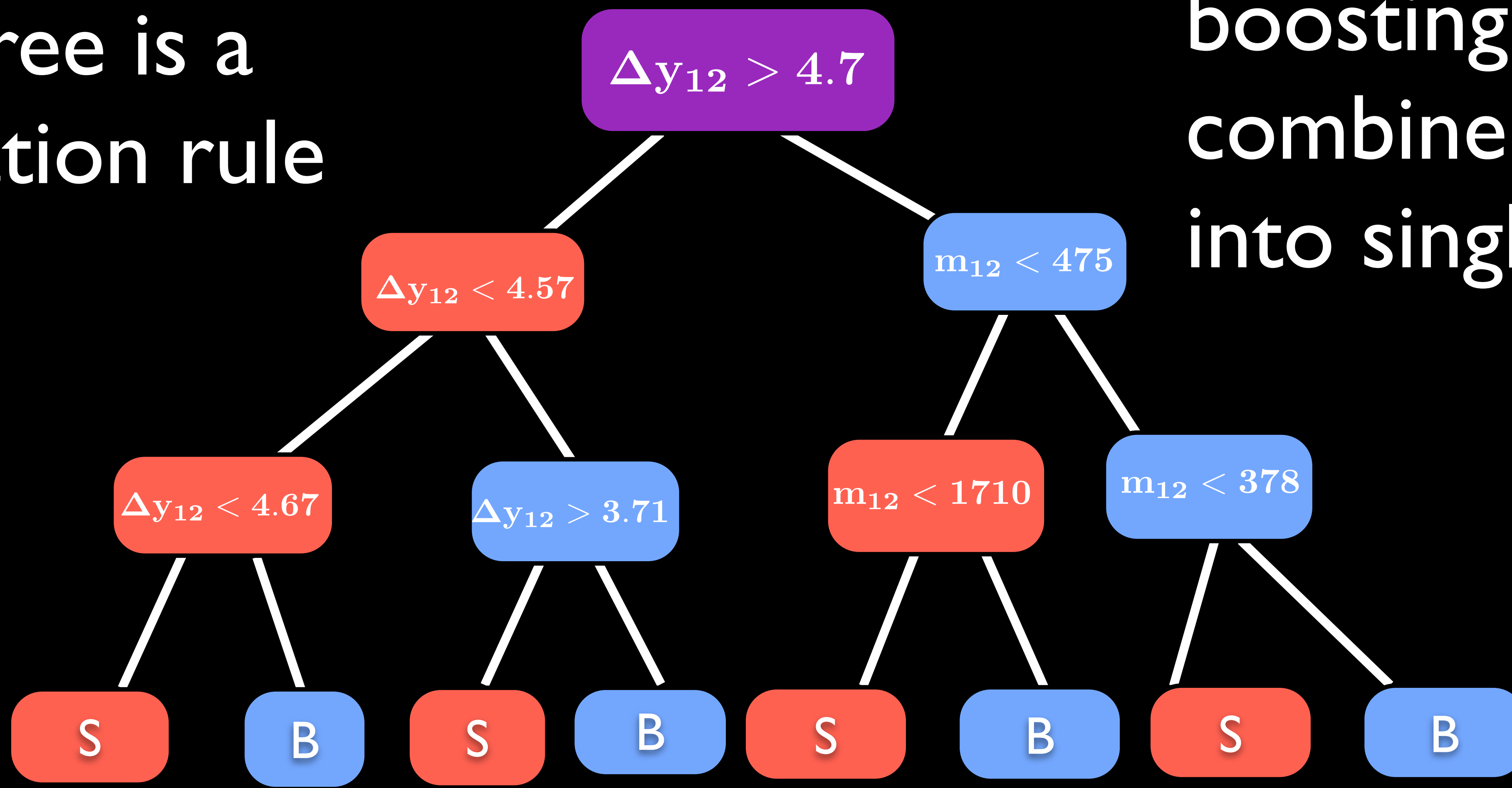
each point on curve corresponds to a cut on classifier response

if $y_{cut} = 0$

$$(\varepsilon_s, r_b) = (1, 0)$$

Boosted Decision Trees

each tree is a classification rule



boosting: combine trees into single rule

Adaptive Boost Algorithm:

$$y(\vec{x}) = \frac{1}{N_{\mathrm{boost}}} \sum_{i}^{N_{\mathrm{boost}}} \ln(\alpha_i) h_i(\vec{x})$$

events misclassified are reweighted, another tree is built, misclassification rate is updated, event is reweighted, etc...

$$h_i(\vec{x}) = +1 \ (\mathrm{sig}), \ -1 \ (\mathrm{bkg})$$

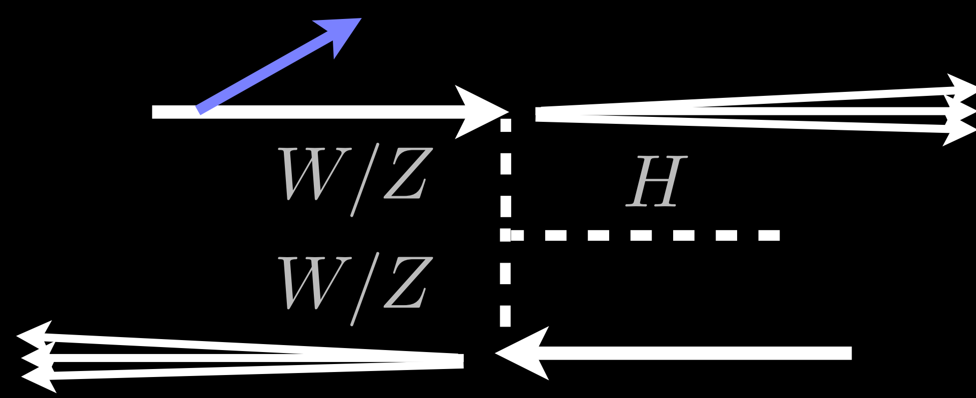
$$\alpha_i = \frac{1 - err_i}{err_i}$$

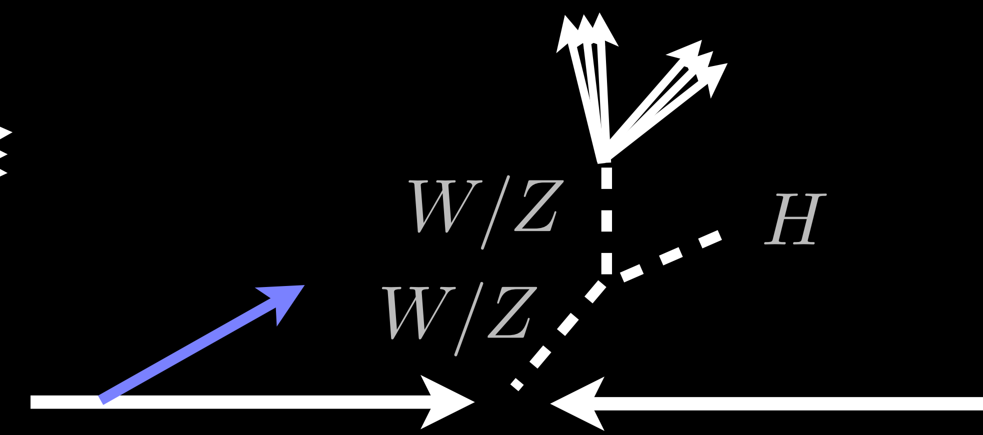
$$err_i = \ \text{misclassification rate}$$

Analysis for H --> diphoton

(process + hard jet) x PS with CKKW using SHERPA

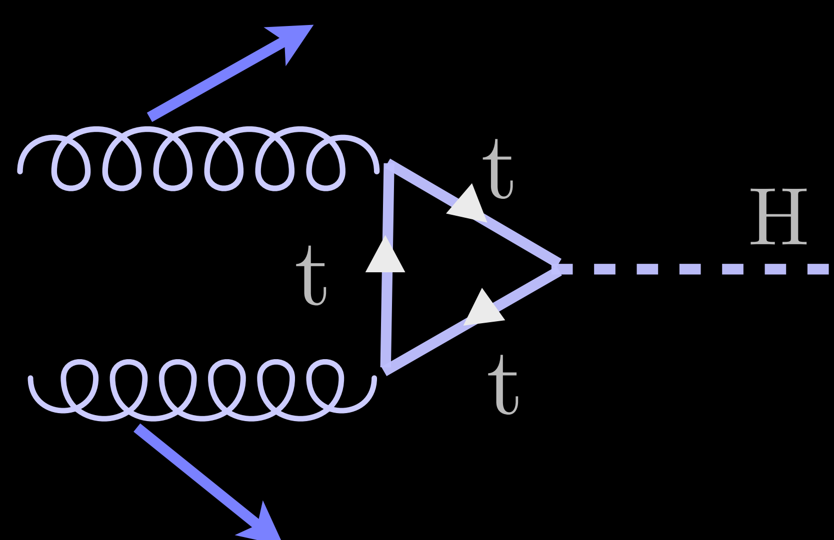
Signal:



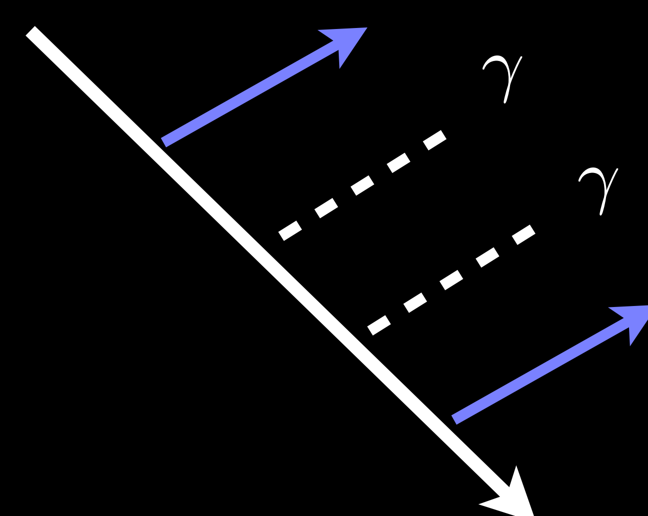


“weak boson fusion” wbf

Backgrounds:



“gluon fusion” ggf



‘continuum’ di-photon

BDT Analysis with only Tagging Jet Correlations

use FWM after applying acceptance criteria for jets:

$$p_{Tj} > 25 \text{ GeV} \quad \text{for} \quad |y_j| < 2.4$$

$$p_{Tj} > 30 \text{ GeV} \quad \text{for} \quad 2.4 \leq |y_j| < 4.5$$

$$|\Delta y_{j_1 j_2}| \geq 2 \quad \text{and} \quad m_{j_1 j_2} > 150 \text{ GeV}$$

compare FWM with tagging jet correlations used by ATLAS

$$\{m_{j_1 j_2}\,,\ y_{j_1}\,,\ y_{j_2}\,,\ \Delta y_{j_1 j_2}\}$$

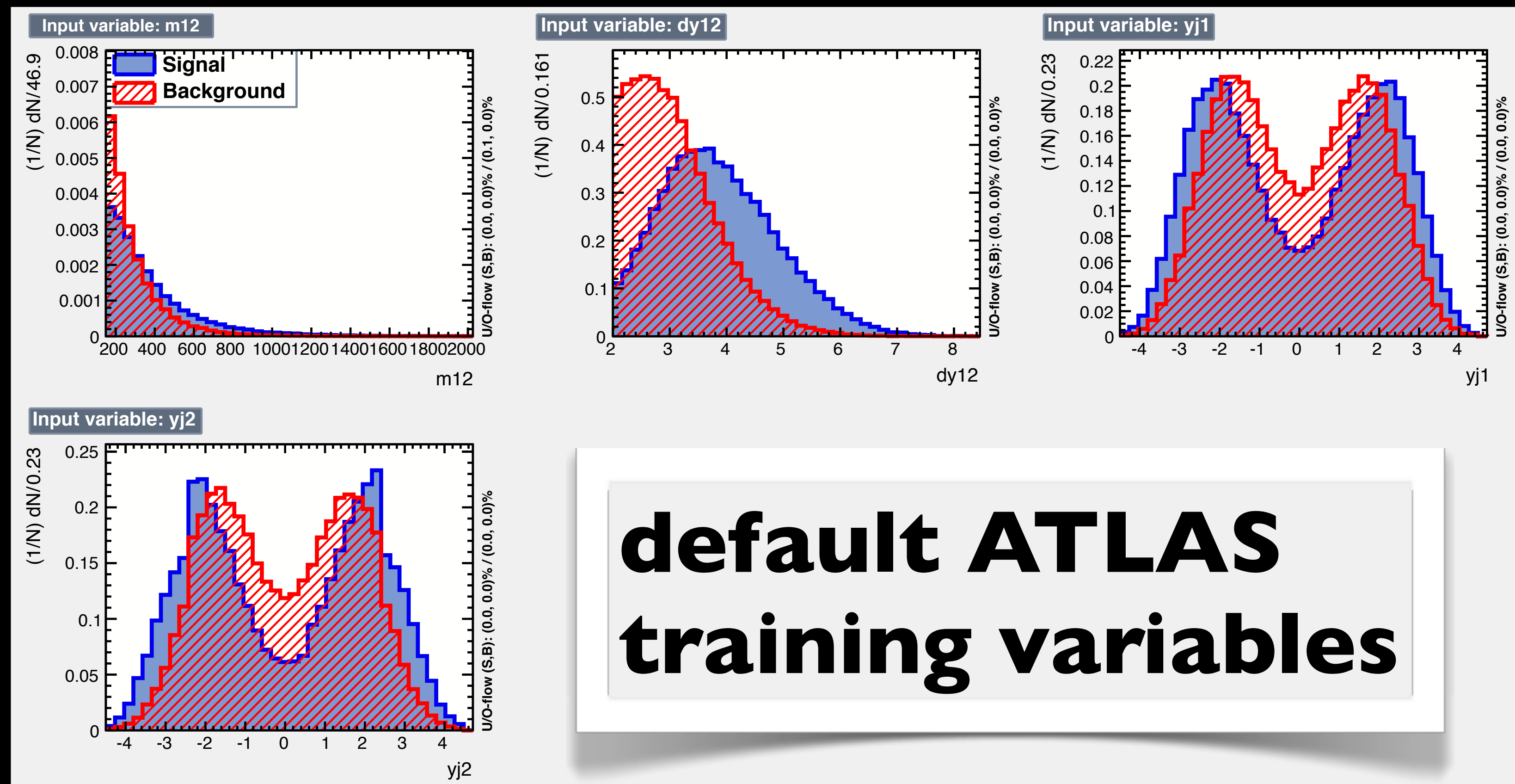
Decision Tree Settings[1]:

N_{train}, N_{test} = 100K, 50K

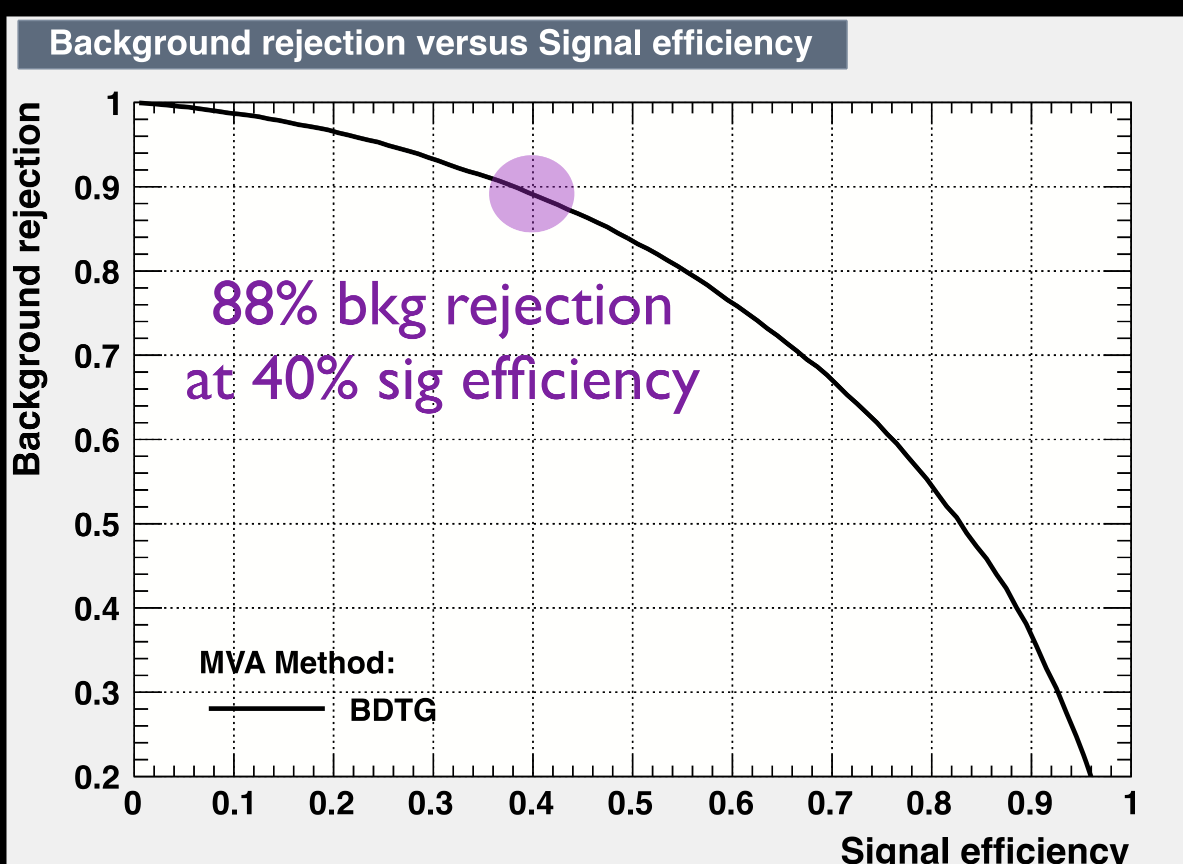
N_{trees}, N_{layers} = 400, 3

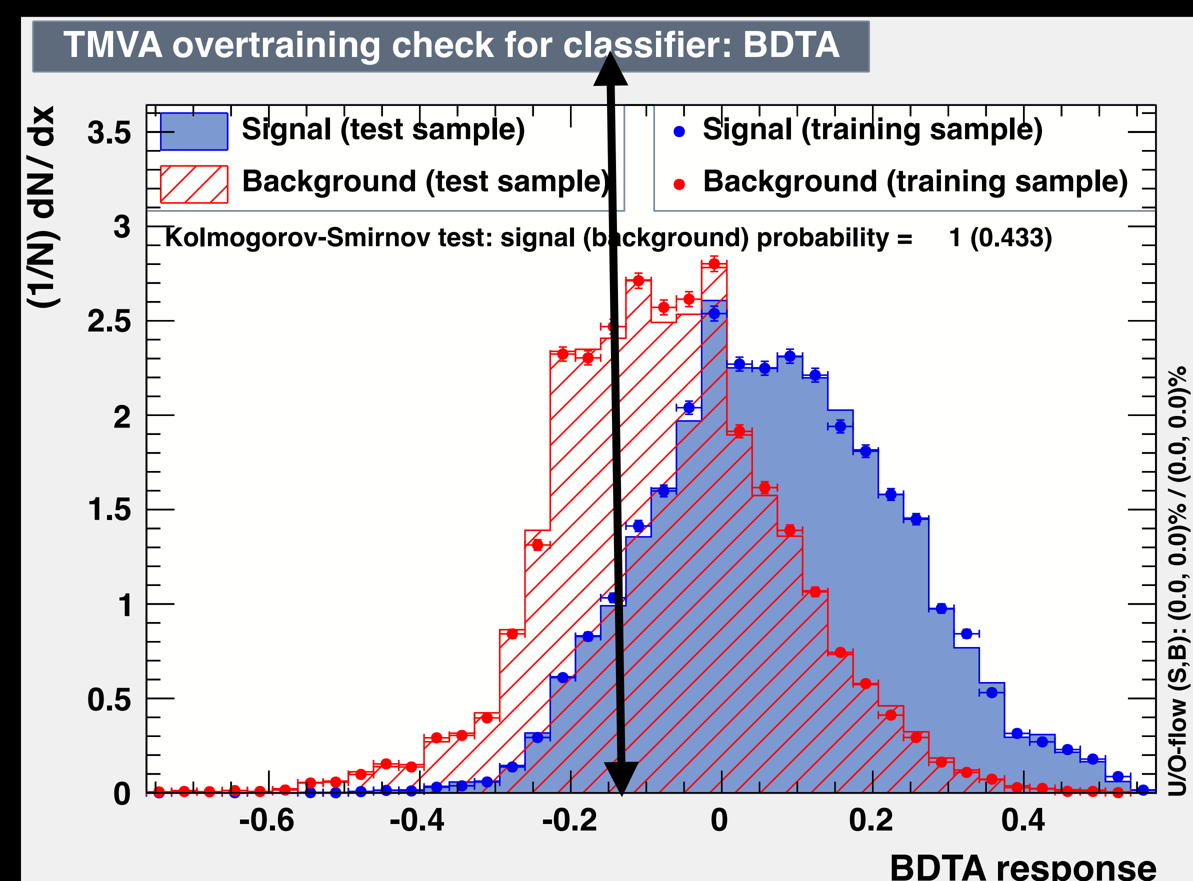
[1] Hoecker et.al. , Toolkit for Multivariate Analysis , http://tmva.sourceforge.net

Results of BDT Analysis Including FWM



default ATLAS training variables





Results of BDT Analysis Including FWM

improvement with redefinition of FWM:

$$H_\ell^{x,\phi} = \sum_{i,j=1}^{N} W_{ij}^x \, P_\ell(\cos \Delta\phi_{ij})$$

	BDT			MLP		
$\epsilon_S = 0.4$	$1 - \epsilon_B$	$\frac{S}{\sqrt{S+B}}$	$\frac{S}{B}$	$1 - \epsilon_B$	$\frac{S}{\sqrt{S+B}}$	$\frac{S}{B}$
ATLAS default	0.887	1.50	0.76	0.888	1.50	0.78
$H_1^{T,\phi} \to H_4^{T,\phi}$, $H_1^{U,\phi} \to H_4^{U,\phi}$	0.952	1.65	1.54	0.953	1.65	1.55
$H_1^{T,\phi}$, $H_3^{T,\phi}$, $H_1^{U,\phi}$, $H_3^{U,\phi}$	0.952	1.66	1.56	0.952	1.65	1.54
$H_1^{T,\phi}$, $H_2^{T,\phi}$, $H_2^{U,\phi}$, $H_2^{U,\phi}$	0.953	1.65	1.47	0.953	1.65	1.55
$H_1^{T,\phi}$, $H_1^{U,\phi}$	0.953	1.65	1.43	0.952	1.65	1.46
$H_1^{T,\phi}$	0.950	1.63	1.45	0.950	1.63	1.44
$H_1^{U,\phi}$	0.952	1.65	1.40	0.952	1.65	1.44
$\cos \Delta\phi_{12}$, W_{12}^T	0.952	1.65	1.53	0.952	1.65	1.50
$\cos \Delta\phi_{12}$	0.952	1.65	1.42	0.952	1.65	1.44

redefinition of FWM offer modest improvement over ATLAS default variables

CB, Mellado, Plehn, Ruan, Schichtel, PRD 89, 05306 (2014)

Results of BDT Analysis Including FWM

- Both MVA analyses with first four moments with each weight reduces remaining fraction of background events by a factor of two

- These eight moments dominate the distinctive power of the analysis

- Individually, the best moments are (in order, based on TMVA ranking) :

$$H_1^{U,\phi}\,,\ H_1^{T,\phi}\,,\ H_3^{U,\phi}\,,\ H_3^{T,\phi}\,,\ H_2^{U,\phi}\,,\ H_2^{T,\phi}$$

- Following this analysis, we suggest to extend the default set of variables to include:

$$m_{j_1 j_2},\ y_{j_1},\ y_{j_2},\ \Delta y_{j_1 j_2},\ \Delta\phi_{j_1 j_2}$$

Summary

- Fox - Wolfram moments constructed from tagging jets offer a significant improvement over current ATLAS analyses

$$H_\ell^T = \sum_{i,j=1}^{2} \frac{p_{Tj_i} p_{Tj_j}}{p_{T\mathrm{tot}}} P_\ell(\cos \Delta\phi_{ij})$$

$$H_\ell^U = \sum_{i,j=1}^{2} \frac{1}{N_{\mathrm{tot}}} P_\ell(\cos \Delta\phi_{ij})$$

$$H_1^{U,\phi}\,,\; H_1^{T,\phi}\,,\; H_3^{U,\phi}\,,\; H_3^{T,\phi}\,,\; H_2^{U,\phi}\,,\; H_2^{T,\phi}$$

Using FWM to Replace Jet Veto

central jet veto = ignore events with rapidity between tagging jets

- Going beyond two tagging jets, can we use FWM to replace a central jet veto? We answer by attempting the following analysis:

(i) generic acceptance cuts $p_{Tj} > 20$ GeV, $|y_j| < 4.5$

$m_{j_1 j_2} > 150$ GeV, $\Delta y_{j_1 j_2} > 2$

(ii) make two different subsets of tagging jets

=> two jets with highest p_T

=> two jets with most forward & backward rapidity y

(iii) further enhance forward-backward geometry - veto level cuts

$$|\Delta y_{j_1 j_2}| > 4.4 \qquad y_{j_1} \cdot y_{j_2} < 0 \qquad m_{j_1 j_2} > 600 \text{ GeV}$$

Using FWM to Replace Jet Veto

	Δy-selection				p_T-selection			
	ϵ_S	$1-\epsilon_B$	$\frac{S}{\sqrt{S+B}}$	$\frac{S}{B}$	ϵ_S	$1-\epsilon_B$	$\frac{S}{\sqrt{S+B}}$	$\frac{S}{B}$
acceptance cuts	1	0	0.76	0.005	1	0	0.81	0.007
veto–level cuts	0.402	0.854	0.80	0.014	0.405	0.996	1.01	0.026
jet veto	0.302	0.967	1.24	0.047	0.369	0.945	1.26	0.045
BDT: WBF default	0.400	0.862	0.79	0.014	0.400	0.904	1.04	0.027
	0.634	0.674	0.84	0.010	0.414	0.897	1.04	0.027
BDT: WBF default plus FWM	0.400	0.952	1.34	0.041	0.400	0.944	1.35	0.047
	0.232	0.986	1.42	0.083	0.302	0.972	1.43	0.071

p_T selection is standard in WBF analyses - but rapidity selection is even better